DEVELOPMENT OF A REVERSE OSMOSIS/ELECTRODIALYSIS PROCESS TO CONCENTRATE NATURAL ORGANIC MATTER

BY

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THESIS

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Abstract

Disinfection in water treatment has been used to protect public health for over 100 years. Disinfectants are added to inactivate pathogens in the drinking water treatment plant and throughout the distribution system. As an unintended consequence, disinfectants react with natural organic matter (NOM) and other background constituents to form disinfection by-products (DBPs). Each disinfectant produces a different range of DBPs. While toxicity effects of many individual DBPs have been studied, the effect of whole-mixtures of DBPs needs further investigation. The overall goal of this project is to develop and optimize a NOM concentration method using a sequential reverse osmosis (RO)/electrodialysis (ED) treatment system that can be used for toxicity studies. This work focuses on data comparison from two methods of NOM concentration and two sources of sample water, Newmark tap water and a filter effluent from a conventionally-treated surface water treatment plant in Central Illinois, IL. Throughout the processing, dissolved organic carbon (DOC), conductivity, $SUVA_{254nm}$, pH and select anions (chloride and sulfate) were monitored. Both conductivity and $SUVA_{254nm}$ increased proportionally throughout processing both the Newmark and Central Illinois water samples. The RO portion of the study was completed successfully but additional work is recommended to implement the ED portion successfully.

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Table of Contents

Chapter One: Introduction

1.1 Motivation

Both surface and ground waters contain natural organic matter (NOM). NOM interacts with chlorine or other disinfectants and produces disinfection by-products (DBPs) at the drinking water treatment process. There are over 600 species of DBPs that have been identified so far in the water treatment processes and throughout the distribution system (Richardson et al., 2007). However, a significant portion of DBPs formed in disinfected water including those contributing to total organic halides remain to be identified (Krasner et al., 2006). Two DBP groups consisting of five haloacetic acids and four trihalomethanes have been regulated by the United States Environmental Protection Agency (USEPA, 2006). Trihalomethanes have been linked to bladder cancer and adverse pregnancy outcomes (Villanueva et al., 2004; Hrudey et al., 2009), and haloacetic acids and several other DBP groups have been found to be cytotoxic and genotoxic to mammalian cells (Richardson et al., 2007).

In vitro mammalian cell toxicity studies have shown that nitrogenous DBPs (like nitrosamines, haloacetamides and haloacetonitriles) are more cytotoxic and genotoxic than the regulated DBP species (Plewa et al., 2008; Plewa et al., 2009; Richardson et al., 2007). However, consumers are exposed to the mixture of regulated and unregulated non-nitrogenous and unregulated nitrogenous DBPs in their drinking water sources. Unfortunately, cumulative toxic effects from exposures to DBP mixtures cannot be addressed from toxicological studies of individual DBPs (Simmons et al., 2002).

Toxicological studies typically use higher DBP concentrations than environmentally relevant levels to detect toxic response. Multiple concentration levels are used to characterize concentration-response relationships. Concentrated DBP mixtures for cyto and genotoxicity evaluations have been prepared by filtering the water through adsorption columns packed with macro-reticular cross-linked aromatic polymers (XAD resins) (Jeong et al., 2012; Plewa et al, 2012). The results from these studies are somewhat inconclusive because of the selective recovery of hydrophobic components and the loss of hydrophilic and volatile fractions. Use of reverse osmosis membranes for studying the toxicity of DBP mixtures has been examined as a means to retain the concentrated organics in a water matrix (Pressman et al., 2010; Simmons et al., 2002; Speth et al., 2008). However, background electrolytes are co-concentrated with NOM, and the resulting ionic strength of the solution would kill the cells used for toxicity experiments. Co-concentrated inorganic salts can be removed using electrodialysis as proposed by Vetter et al. (2007) and Gurtler et al. (2008). The present study investigates a hybrid reverse osmosis/electrodialysis process as a means of concentrating NOM that could be subsequently disinfected to produce DBPs and used for toxicity studies.

1.2 Objective

The objective of this project was to develop and optimize a process that would concentrate the natural organic matter (NOM) in treated surface water suitable for subsequent toxicity tests. A reverse osmosis/electrodialysis combination was used. Due to performance issues with the electrodialysis unit, this project emphasizes data from the RO system setup.

Chapter Two: Literature Review

2.1 Natural Organic Matter (NOM)

Natural organic matter consists of a broad range of organic molecules produced in the natural environment. The complex NOM mixtures contain molecules of varying molecular weights, elemental composition and acidic functional groups (Shapiro et al 1957, Chin et al 1994). NOM can exist in the form of particulates, colloids and dissolved matter. The dissolved NOM is most commonly quantified as dissolved organic carbon (DOC). Fractions of NOM that contribute to DBP formation include hydrophobic and hydrophilic acids, and compounds of low and high molecular weights (Leeheer et al., 2003, Hua et al., 2007).

2.2 Reverse Osmosis (RO)

Reverse osmosis (RO) is a membrane process that uses hydraulic pressure to separate water from the feed solution. Of the pressure-driven membrane processes (microfiltration, ultrafiltration, nanofiltration and reverse osmosis), RO has the smallest characteristic pore diameter. Accordingly, RO has the ability to separate the smallest molecules and ions and from water among the pressure-driven membrane processes. Reverse osmosis has been used for a number of water quality control applications including: sea and brackish water desalination, softening, NOM removal for DBP control, and water reuse (Crittenden et al, 2012). Aside from water treatment, RO has also been used for recovering NOM (Koprivnjak et al., 2006, Vetter et al., 2007, Gurtler et al., 2008, Kilduff et al 2004, Speth et al., 2008, Sun et al., 1994, Serkiz et al., 1990).

The flux of permeate water (J_v) across an RO membrane element can be described by equation 2.1 (Benjamin et al., 2013).

$$J_v = A(\Delta P - \Delta\pi) \qquad \text{Equation 2.1}$$

Where K_v is a coefficient that depends on the water quality (hereafter labeled as A), ΔP is the hydraulic pressure difference (i.e., the hydraulic pressure supplied to the system minus that in the permeate), and Δπ is the osmotic pressure difference (i.e., the osmotic pressure of the feed solution next to the membrane wall minus that of the permeate).
Multiplying both sides of equation 2.1 by the total surface area of membrane (S) gives an expression (equation 2.2) for the permeate flow rate (Q_p).

$$Q_p = SA(\Delta P - \Delta\pi) \qquad \text{Equation 2.2}$$

2.3 Electrodialysis

Electrodialysis (ED) is a combination of electrolysis and dialysis where ions are transferred across an ion selective membrane by an electrical potential (Figure 2.1). Whereas RO is a pressure-driven membrane process, ED is a membrane process driven by an electrical potential difference. The flux rate of desalting, described by the Nernst-Planck Equation (Equation 2.3), depends on the rate of molecular diffusion ($-D_i \frac{dC_i}{dz}$), electrotransport ($-D_i \frac{z_i C_i F}{RT} \frac{d\varphi}{dz}$) and convection ($+v_k C_i$) (Strathmann 2004). Additionally, the overall rate of desalting depends on the total surface area of the flow path.

$$J_i = -D_i \frac{dC_i}{dz} - D_i \frac{z_i C_i F}{RT} \frac{d\varphi}{dz} + v_k C_i \qquad \text{Equation 2.3}$$

where J_i is flux, D_i is the molecular diffusion coefficient, C_i is the concentration, and z_i is the charge of ionic species i. φ is the electrical potential, v_k is the convective flux, F is the Faraday constant, R is the ideal gas constant, T is absolute temperature, and z is a directional coordinate.

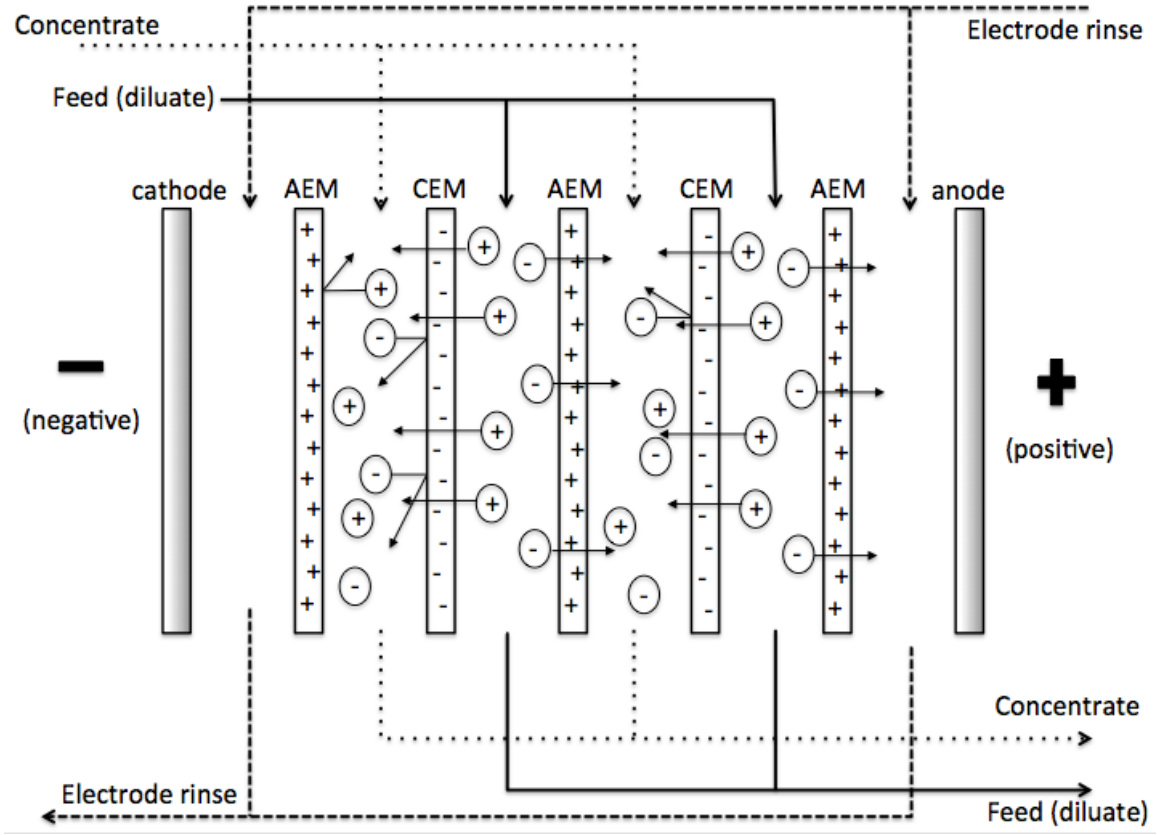

Figure 2.1: Transport of ions from the feed solution into the concentrate solution (adapted from Benjamin et al., 2013). The anion exchange membranes and the cation exchange membranes are called AEM and CEM, respectively.

An ED membrane stack (Figure 2.2) consists of a number of cell pairs. Each cell pair is made of an ion exchange membrane that is preferably permeable towards anions (anion exchange membrane) and another that is preferably permeable towards cations (cation exchange membrane), separated by flow spacers for the diluate and concentrate solutions (Figure 2.3). The ion exchange membranes are made of a polymer matrix with incorporated charged functional groups (Table 2.1, Strathmann 2004). Ion exchange properties of the anion exchange membranes can lead to NOM fouling (Lindstrand et al., 2000) and a loss of NOM in the water sample. The ion-exchange membranes used in this research contain strong acidic and basic functional groups. The functional groups used for the ion exchange membranes will affect their selectivity for monovalent (in this case NOM) or divalent ions (Boari et al., 1974).

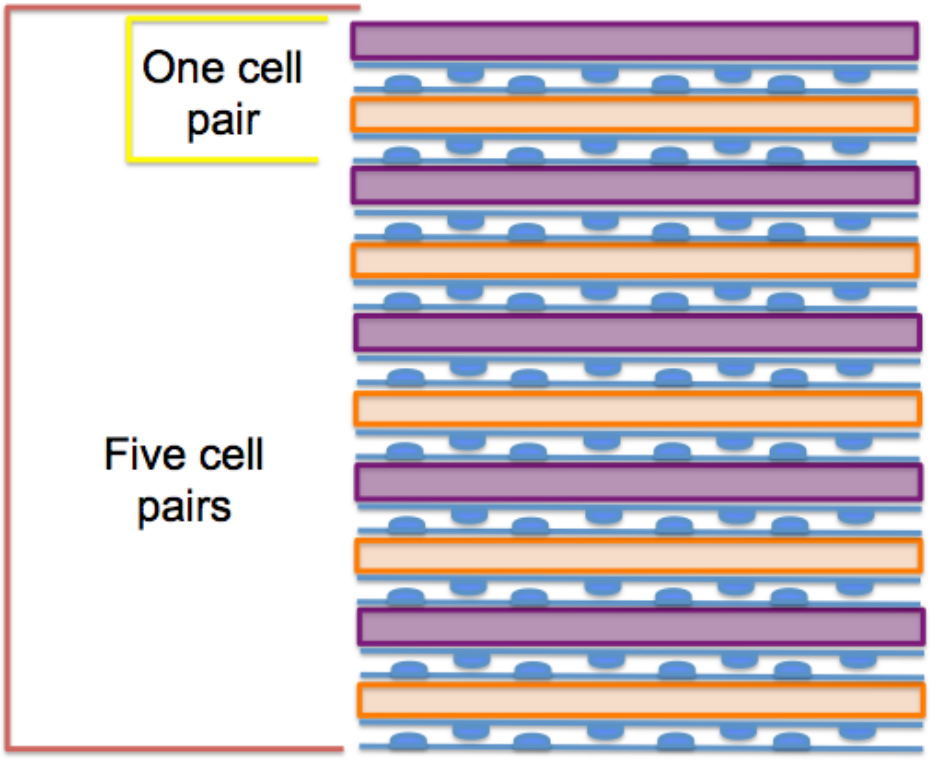

Figure 2.2: ED Membrane stack consisting of five cell pairs.

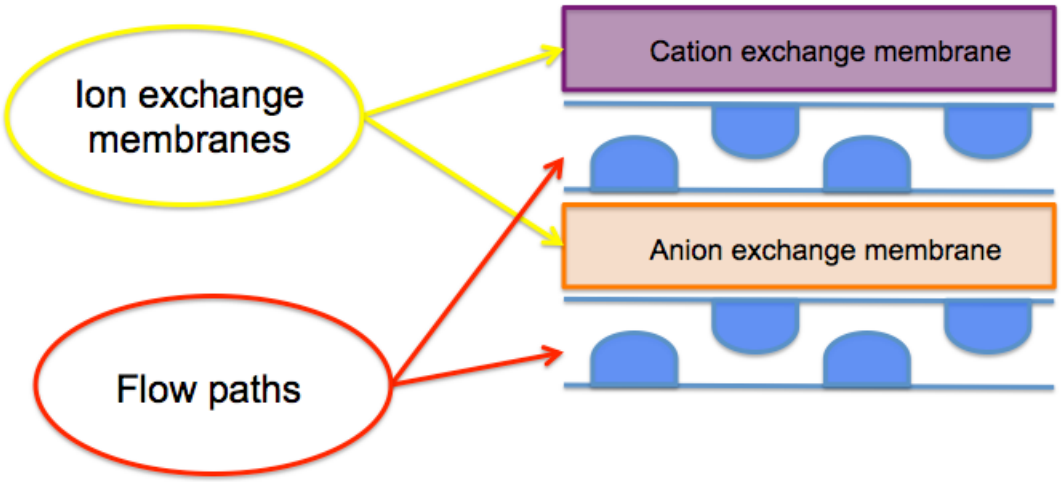

Figure 2.3: An anion exchange membrane separated by two spacers (flow paths for the diluate and the concentrate).

Table 2.1: Options for charged functional groups for ion-exchange membranes (Strathmann 2004).

Ion-exchange membrane type	**Charged functional group type**	**Strong**	**Weak**
Cation exchange membrane (CMX)	Acidic	Sulfonic	Carboxylic
Anion exchange membrane (AMX)	Basic	Quaternary Amine	Tertiary Amine

2.4 NOM Recovery Using RO/ED

The hybrid RO/ED configuration used in this study was inspired by those used in the collaborative efforts of researchers from Georgia Tech and Kansas State University. The aim of this group was to concentrate natural organic matter to study global carbon cycle (Koprivnjak et al., 2006; Vetter et al., 2007; Gurtler et al., 2008; Koprivnjak et al., 2009). They needed large quantities of freshwater and marine NOM samples with low ash that could be freeze-dried and subsequently analyzed and transported with ease. Their

approach was to concentrate NOM using reverse osmosis (RO) (for the concentration of NOM) and electrodialysis (for the removal of the co-concentrated salt species). However, their application differs from the aim of this project because the goal of this project is to retain NOM in aqueous matrix at the highest possible concentration for use in subsequent disinfection and toxicity studies.

Koprivnjak et al. (2006) used the tandem RO/ED process to concentrate NOM from two surface water sources. They used concentrated natural river water and synthetic concentrated river water to examine the effects that water chemistry (pH, conductivity as well as concentrations of silicic acid and sulfate) and operating conditions (voltage, active surface area of ED membranes, etc.) had on the removal rate of sulfate and the retention percentage of NOM. First, they used synthetic water samples to determine that sulfate removal, and retention of NOM was best at pH > 6 and conductivity > 1.0 mS/cm. The second set of experiments involved the processing of south Georgian surface waters from the Suwannee and Withlacoochee rivers. Both source waters were first processed using H^+ cation exchange to remove precipitate-forming cations. This was followed by ED treatment for salt removal. After the electrodialysis processing, Koprivnjak et al. (2006) retained 94% and 88% of the DOC from the Suwannee and Withlacoochee rivers, respectively, while achieving 65% and 79% removal of the silica and sulfate.

Whereas Koprivnjak et al. (2006) applied tandem RO/ED process on freshwater NOM, Vetter et al. (2007) and Gurtler et al. (2008) used the coupled RO/ED configuration to concentrate and desalt samples of marine NOM. Both Vetter et al. (2007) and Gurtler et al.

(2008) used the knowledge gained from Koprivnjak et al. (2006) as a baseline for ED operation.

For Vetter et al. (2007), seawater was passed through a 0.45 μm filter then stored in a 210 L tank. The cylindrical tank had a conical bottom and was made from high-density polyethylene (HDPE). The seawater was processed with an ED phase followed by a RO/ED phase and finally an ED phase. Vetter et al. (2007) used an initial electrodialysis phase to remove ~70% of salt ions. After the initial electrodialysis phase, a concurrent RO/ED phase was used to remove ~80% of water and an additional ~15% of salt ions. The final ED phase was the source of the greatest loss of NOM due to ion exchange of NOM onto the surface of the anion exchange membranes. Gurtler et al. (2008) showed that maintaining the conductivity above 15 mS/cm ensures that salt species will outcompete NOM for ion exchange sites on the anion exchange membranes.

The work by Gurtler et al. (2008) is a continuation of Vetter et al. (2007) with some modifications. They used the same setup with the addition of a baffle installed into the outlet of the cylindrical tank. This baffle covered the effluent to the RO and eliminated the development of vortexes in the system. Vortexes are problematic because they can introduce air into the lines and damage the pumps and RO membranes. The most notable modification was the introduction of a "relaxation time" for the final ED phase. Pulsing the ED current generated the relaxation time. They showed that a relaxation time of two seconds can result in an increased salt removal without losing NOM; this was compared to ED processing without the pulsed current (Gurtler et al., 2008).

Their data showed a percent yield of NOM (measured as DOC) of ~68±5%. This excluded an outlying sample that had a percent yield of NOM of 95%. This outlier introduced a variable into the dataset because it was collected at a depth classified as deep ocean waters (>200 m); the other samples were collected within the surface ocean waters (<200 m) range of depth. So, although they demonstrated that NOM recovery could be as high as 95%, it is safe to expect 60-70% recovery of NOM from our process.

The mass balances performed by this research team were described with more detail in Koprivnjak et al. (2009). For all samples, they retained an average of 75 % of the NOM, which included both the NOM that remained in solution at the end of the process and the NOM that was recovered from both RO and ED membranes with NaOH rinse. The ED with and without pulse achieved comparable NOM retention while further removal of salt was achieved with pulsation. They monitored the NOM concentration in the diluate, concentrate and permeate tanks and concluded that the unrecovered NOM was due to adsorption onto the ED membranes during the final ED stage.

In addition to information about mass balances of NOM, Koprivnjak et al. (2009) analyzed changes in chemical and spectroscopic characteristics of NOM by using ultraviolet-visible (UV/Vis) absorbance spectroscopy to calculate the Specific Ultraviolet Absorbance (SUVA). Both the UV/Vis spectra and the SUVA at 300 nm were used to observe changes in the chromophoric dissolved organic matter (CDOM; a chromophore is the part of the molecule responsible for light absorption).

Five samples from the RO/ED experiments were analyzed for UV/Vis spectra before and after processing. For each of the five samples, the normalized absorption coefficient ($a(\lambda)/a(290)$) values versus wavelength yielded comparable plots between the RO/ED samples and their respective source seawaters (Koprivnjak et al. 2009). This finding suggested that the CDOM content of the samples was retained, and supported that RO/ED process did not change the chemical quality of the NOM significantly.

Chapter Three: Materials and Methods

3.1 Reverse Osmosis System

The reverse osmosis membrane used for these experiments was a Dow Filmtec spiral-wound element model TW30-2540 (Dow Chemical Company, Midland, MI). The TW30 series is designed for brackish water treatment and was chosen because it was used successfully in previous work (Gurtler et al., 2008; Koprivnjak et al., 2006; Tu et al., 2012; Vetter et al., 2007). Details about the membrane element properties and performance are summarized in Table 3.1. Two types of pressure vessels were used.

Table 3.1: Characteristics of Dow Filmtec TW30-2540 reverse osmosis element.

Parameter	Value with units
Dimension of element	2.4 in. x 40 in (dia. x length)
Active surface area	2.60 m^2
Maximum feed pressure	600 psig
Maximum pressure drop per element	13 psig
Permeate flow rate[1,2]	2.22 L/min
Stabilized salt rejection[1]	99.5 %

[1] Based on 2000 ppm NaCl feed solution, 225 psig and 15% permeate recovery
[2] Permeate flow rate can vary up to ±20% by individual element

The general approach in the RO operation was to pump the water in the process tank through the reverse osmosis membrane and return the concentrate to the process tank. A CAT Pumps model 341 plunger pump (CAT Pumps, Minneapolis, MN USA) was used. The RO permeate was collected, weighed and recorded for mass and time of collection to determine the flow rate. An OHAUS DS4 gravimetric scale (20 kg max) was used for weight measurements. The temperature in the process tank water was controlled at 20^{o}C by a

VWR Recirculator. Two operation modes were used: decreasing volume and constant head operations (discussed later).

3.2 Reagents

Unless stated otherwise, all reagents were purchased from either Fisher Scientific (Fair Lawn, NJ) or Sigma-Aldrich Company (St. Louis, MO).

3.3 Analytical Techniques

The total organic carbon (TOC) content was measured using a Shimadzu TOC-VCPH oxidation/combustion TOC analyzer (Shimadzu Scientific Instruments, Columbia, MD). The concentrations of sulfate and chloride were quantified using a Dionex ion chromatography system (Dionex, Sunnyvale, CA) with a Dionex IonPac™ AS-19 column and a Dionex IonPac™ AG19 guard column. The eluent was either 10 mM or 22 mM KOH. The flow rate was 1.0-1.2 mL/min. The absorbance at 254 nm (UVA_{254nm}) was determined by a Shimadzu UV-2550 UV/Vis spectrophotometer (Shimadzu Scientific Instruments, Columbia, MD). Conductivity and temperature were measured using a EUTECH Alpha COND 500 meter and a Cole-Parmer brand temperature probe (model EW-19500-45). Two conductivity probes were used, one with a cell constant (k) of 1.0 and another with a cell constant (k) value of 10. The pH was determined by an Orion 420A bench top meter equipped with a Fisher Scientific Accumet probe (model 13-620-631). The alkalinity and the concentration of calcium were determined using a Hach digital titrator following Hach methods 8203 and 8204, respectively.

3.4 Summary of Operations of RO System

The experiments performed were designed based on previous work reported by Tu (2012). Tu examined the concurrent RO/ED operation proposed for seawater NOM recovery by Gurtler et al. (2008), but their methodology did not work for tap water since the salinity of tap water is much lower compared to that of seawater. Tu explored a strategy to concentrate tap water first with RO followed by demineralization by ED, and concluded that a much larger quantity of water needed to be processed with RO before ED being applied to prevent NOM adsorption onto the ED membranes. Two setups were developed and examined in this work (Figures 3.1, 3.2).

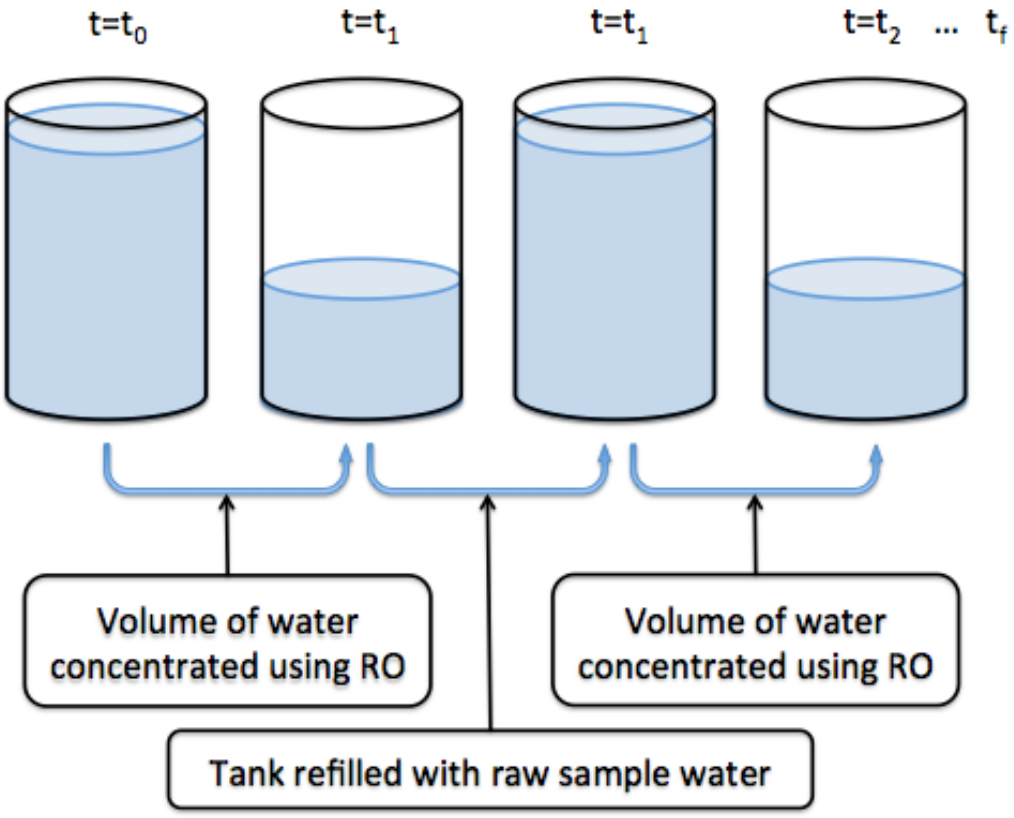

Figure 3.1: Description of decreasing volume operation.

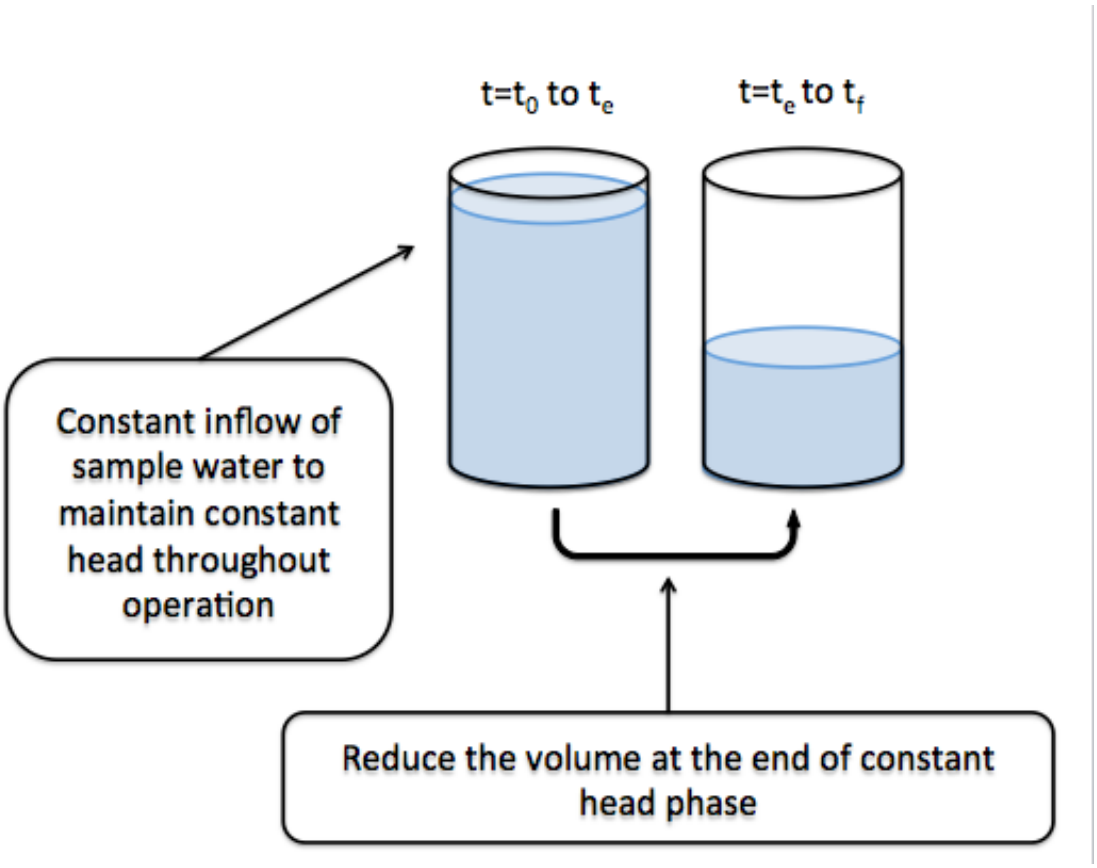

Figure 3.2: Explanation of constant head operation.

3.4.1 Setup and Operation for Decreasing Volume Experiments

Figures 3.3, 3.4 and Table 3.2 illustrate the pilot-scale RO system for decreasing volume configuration. The process tank was filled using tap water from Newmark Civil Engineering Laboratory room 4216 (laboratory where the experiments were conducted). Before going into the process tank, water from the tap was processed through the ion exchange unit to remove divalent cations. After filling the tank, a water sample was taken and the height of water was recorded. To begin an experiment, the reverse osmosis pump was started. The ion exchange column was packed with 50 lbs of ZeoPrep® inorganic zeolite with an ion exchange capacity of 1.83 meq/gram (Miracle Water/EcoWater, Urbana, Illinois). The

zeolite was rinsed and regenerated periodically by flushing deionized water through a regeneration tank containing 1 kg of reagent grade NaCl. A rinse cycle lasted for one hour. The softened water was then pumped to successive microfiltration processes through 1.0 μm and 0.3 μm cartridge filters (Millipore®), and into the process tank. Then, the water was dechlorinated by adding 4 mL of a 2.5 M sodium bisulfite solution. The filtered, dechlorinated water in the process tank water was pumped through the TW30-2540 RO membrane and back to the process tank (Figures 3.3, 3.4; Table 3.2). The pressure vessel used was a 600 psi-rated, stainless steel unit (model PV2540SSAW-316). Later, the unit was replaced with a 1000 psi-rated, fiberglass unit (model F2540-14141000C). Both units were purchased from Applied Membranes (Vista, CA USA). The RO unit was operated until the volume of the water in the process tank decreased from 180 L to 30 - 100 L. An Equilibar EB2NL2 backpressure regulator (Equilibar, LLC; Fletcher, NC) was used to control the permeate flow rate. Permeate was collected in 20 L high density polyethylene carboys. The height of water in the process tank decreased over time due to the permeate flux and zero inflow of raw water. As the height decreased, the concentration of salt species and NOM increased as well as the osmotic pressure. At the conclusion of each cycle, the process tank was refilled with filtered water to make up a total volume of 180 L, approximately. Water samples from the process tank, and online water quality data (pH, conductivity, temperature and the transmembrane pressure (ΔP), were collected at regular intervals throughout the experiments.

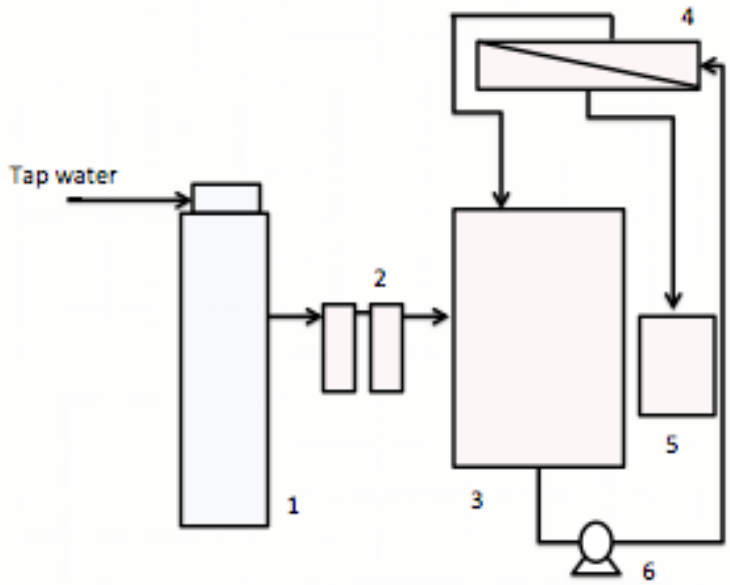

Figure 3.3: Reverse osmosis system used for decreasing volume operation (numbered components defined in Table 3.2).

Figure 3.4: Pilot lab system for decreasing volume experiments (permeate collection is not shown) (numbered components defined in Table 3.2).

Table 3.2: Components of reverse osmosis system in Figures 3.3 and 3.4.

Item number	Description
1	Ion exchange column
2	Microfiltration cartridges
3	Process tank
4	Reverse osmosis membrane
5	Permeate collection tank
6	Pump

3.4.2 Setup and Operation for Constant Head Configuration

The permeate flux is a function of the ionic strength. As the NOM (and ionic species) are concentrated over time, the ionic strength increases and the corresponding increase in osmotic pressure results in a gradual reduction of the permeate flux during each cycle for the decreasing volume configuration. To minimize this decrease in the permeate flux over time, the volume of water in the process tank was maintained close to 180 L (adapted from Kilduff et al., 2004). With the height of water fixed, the increase in salt species (and osmotic pressure) over time would increase at a slower rate than during the decreasing volume experiments. A slower rate of decline in permeate flux means less time was needed to process any given volume of water. In the set of constant head experiments using Newmark tap water, the RO pressure vessel was upgraded from a 600 psi-rated, stainless steel unit (model PV2540SSAW-316) to a 1000 psi-rated, fiberglass unit (model F2540-14141000C) after t = 6000 minutes. Both units were purchased from Applied Membranes (Vista, CA USA). The upgrade was needed due to the decrease in permeate flow rate as a result of an increase in osmotic pressure and irreversible fouling.

Figures 3.5 and 3.6, and Table 3.3 illustrates the constant head configuration. Both Newmark tap water and filter effluent from the Central Illinois water treatment plant were processed with this configuration. The raw water was stored in two 55-gallon stainless steel drums (for experiments using Newmark water, 4 mL of sodium bisulfite were added to each drum to quench the chlorine). The raw water sample, in the 55-gallon stainless steel drums, was continuously pumped through the ion exchange and microfiltration pretreatment and into the process tank (Figures 3.5 and 3.6). An initial sample was collected from the process tank after quenching, and pre-processing with ion exchange and microfiltration. The filtered, dechlorinated water in the process tank was pumped through the RO membrane (TW30-2540) and back to the process tank. To run an experiment, both the inflow and reverse osmosis (RO) feed pumps were started. Water samples were taken from the process tank. Water quality data (pH, conductivity, temperature and ΔP) were also recorded. Pressure gauges were installed before and after each microfiltration cartridge to monitor pressure differences and to indicate when to replace units.

The volume in the process tank was kept constant (using the level control system described below in Section 3.4.3) during the first part of the run. After a period of constant volume operation, the inflow of raw water was stopped, and the water volume in the process tank was reduced to further concentrate NOM.

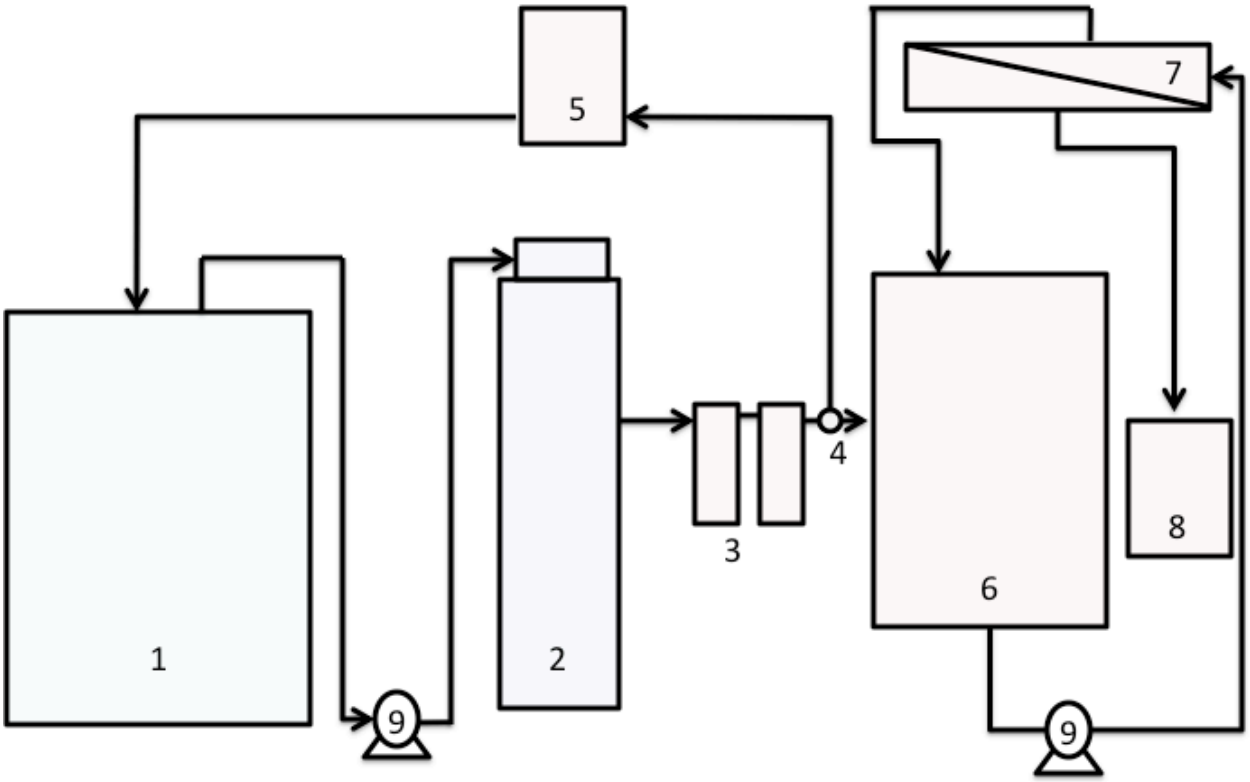

Figure 3.5 Reverse osmosis system with LED sensor controlled flow (numbered components defined in Table 3.3).

Figure 3.6: Pilot lab system for constant volume experiments (Flow control setup and microfiltration cartridges are not shown) (numbered components defined in Table 3.3).

Table 3.3: Components of reverse osmosis system in Figures 3.5 and 3.6.

Item No.	Description
1	Unprocessed sample stored in 55-gallon stainless steel tanks
2	Ion exchange column packed with ZeoPrep® Zeolite (capacity=1.83 meq/g)
3	Microfiltration filters; 1.0 µm cartridge followed by 0.3 µm cartridge
4	Flow control setup (See Figure 3.7 for description)
5	Reservoir for sample water
6	Process tank
7	Reverse osmosis membrane
8	Carboy for permeate collection
9	Inflow or RO Feed Pump

3.4.3 Level-sensing Setup

The volume in the process tank was held constant by controlling the inflow into the process tank using a level sensing system. The level sensing system consisted of three components: An ASCO "Red Hat" solenoid valve, and a GEM optical sensor, and a signal controller (see Figure 3.7, Table 3.4). The solenoid valve was connected to the process tank via a 3/8" bulkhead fitting. The solenoid valve was electrically connected to the controller. The optical sensor was installed approximately one inch from the top of the process tank and was electrically connected to the controller. When the water level reached the optical sensor, a signal was sent to the controller (acting as a relay). The controller closed the solenoid valve and flow into the process tank was diverted to the reservoir (Figure 3.5). In the reservoir, the raw sample water was directed back to the 55-gallon drums by gravity.

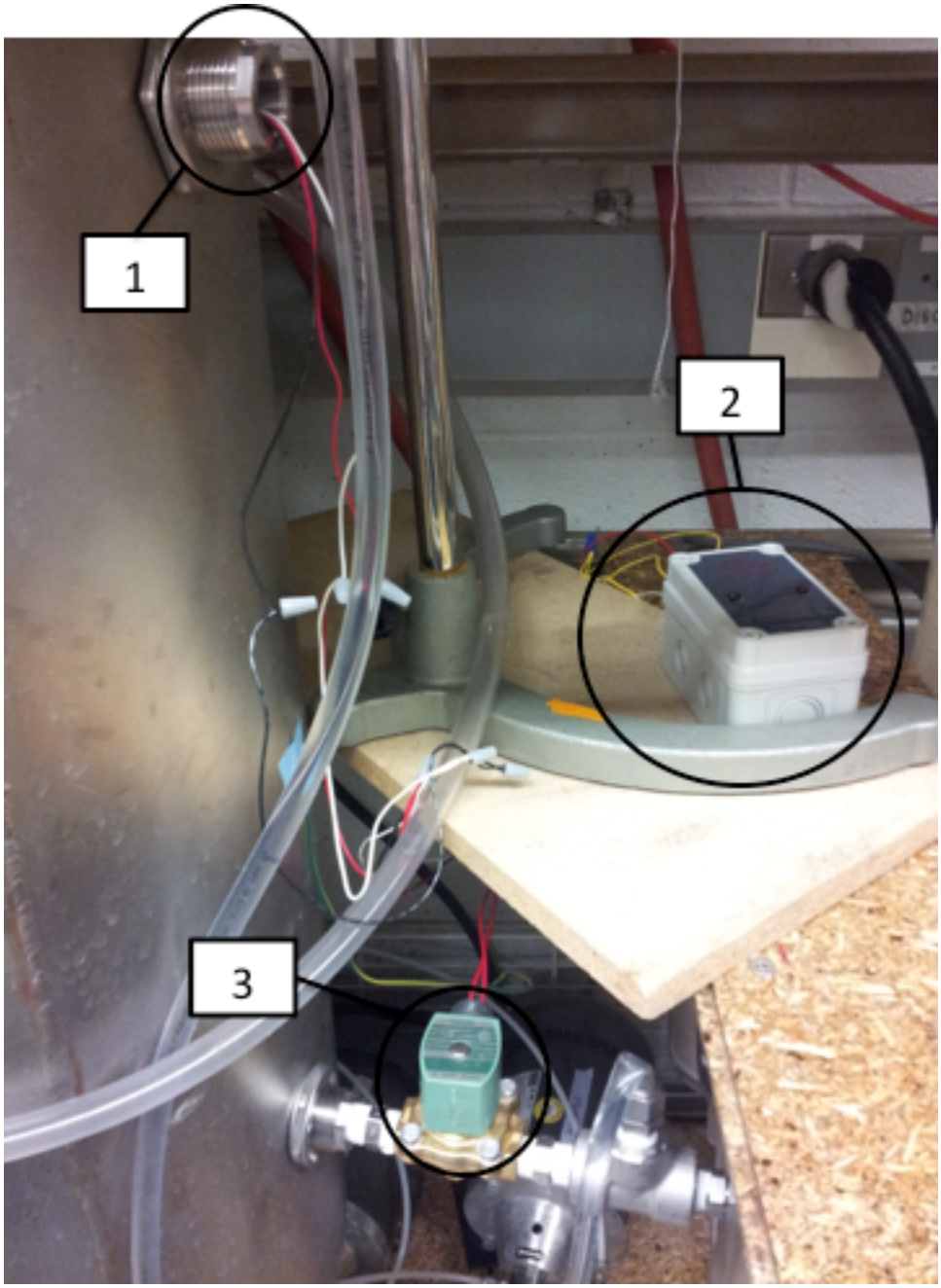

Figure 3.7: Level sensor setup (numbered components defined in Table 3.4).

Table 3.4: Components of level sensing setup in Figure 3.7.

Item No.	Description
1	GEM level sensor
2	GEM controller
3	Red Hat solenoid valve

3.5 Summary of Operations for Electrodialysis System

3.5.1 Setup

Figure 3.8 and Table 3.5 illustrates the ED system setup. The electrodialysis stack was obtained from GE Water & Process Technologies (Trevose, PA). The stack contained 5 cell pairs of alternating AR204SZRA anion exchange membranes and CR67HMR cation exchange membranes. The characteristics of the ED membranes are listed in Table 3.6 (GE Water & Process Technologies, personal communication). The membrane spacer was the Mark I type and was used for all flow channels. The ED stack can be operated as a stand-alone process or simultaneously with the RO process.

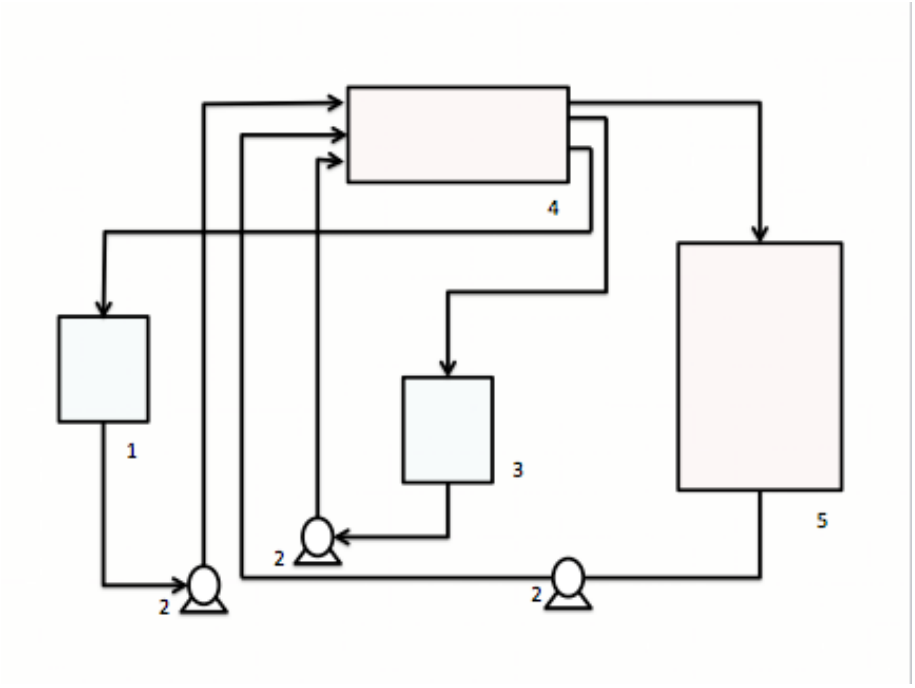

Figure 3.8: Electrodialysis system (numbered components defined in Table 3.5).

Table 3.5: Components of the electrodialysis system in Figure 3.8.

Item Number	Description
1	Concentrate tank
2	Pump
3	Electrode rinse tank
4	Electrodialysis stack
5	Process water tank

Table 3.6: GE ion exchange membrane characteristics.

ED Membrane Characteristic	AR204SZRA anion exchange membrane	CR67HMR cation exchange membrane
Thickness (mm)	0.55-0.60	0.60-0.65
Active membrane area (cm^2)	280	280
Initial membrane resistance (ohm-cm^2)	7-8	9-11
Capacity (eq/L)	1.18	1.08
Functional group	Quaternary ammonium ions	Sulfonate groups

The concentrate tank was filled with 20 L of 0.1 M NaCl solution. The ionic strength of the concentrate stream helped maintain the current across the stack. If the concentrate solution was made with deionized water only (which is not conductive), there would be an impedance of current. The electrode rinse tank was filled with 20 L of a 2% Na_2SO_4 solution. The voltage (and resulting current) for the electrodialysis system was generated by an Ametek DCS 100-10E power supply (100 VDC, 10 A). The voltage applied to the stack ranged from 2 VDC to 10VDC (constant voltage mode).

Three solutions were recirculated through the electrodialysis stack simultaneously during operation: the electrode rinse, concentrate and the process tank water. It was expected that the conductivity of the diluate stream would decrease over the process time and the conductivity of the concentrate stream would increase over time. The three tanks were

connected to separate Fluid-o-Tech MG200 series gear pumps. A WEG CFW10 inverter regulated each flow rate.

3.5.2 Protocol

In previous work, the electrodialysis stack was operated using 30 cell pairs (Tu et al., 2012). The number of cell pairs was reduced to 5 cell pairs ($1/6^{th}$ the initial volume in the stack) or 10 cell pairs. Proportionally, the flow rates for the concentrate and process tank (feed) water channels were scaled down to $1/6^{th}$ of the original values (See Table 3.7).

Table 3.7: Changes in flow rates as a result of reducing the number of cell pairs.

Flow channel	**Flow rate (L/min) for 30 cell pairs**	**Flow rate (L/min) for 5 or 10 cell pairs**
Electrode rinse	0.7	0.7
Concentrate	0.7	0.25
Dilute (feed)	1.3	0.25

Either the concentrated Newmark water sample or NaCl solution was pumped through the diluate stream to observe salt removal over time. The duration of ED operation ranged from 20 to 240 minutes. Samples were taken periodically from the diluate reservoir and the conductivity was measured. The applied voltage and the current were changed with subsequent ED system runs.

3.6 Processed Waters

3.6.1 Newmark Civil Engineering Laboratory Water

Tap water from the Newmark Civil Engineering Laboratory (NCEL, Urbana, IL) was used for both decreasing volume configuration and one of the constant head configuration

experiments. For the decreasing volume experiments, the water from the tap water faucet in NCEL 4216 was directly sent to the ion exchange column followed by microfiltration filters and into the process tank. At the end of each cycle in the decrease volume operation, the process tank was refilled with filtered Newmark tap water, where 4 mL of sodium bisulfite was added to quench residual chlorine.

For the constant head experiments, Newmark tap water was first pumped into 55-gallon stainless steel drums, where 4 mL of sodium bisulfite per 55-gallon was added for dechlorination. The dechlorinated water was pumped through the pretreatment process and into the process tank.

3.6.2 Central Illinois Water Treatment Plant

Filter bed effluent from the Central Illinois Water Treatment Plant (BWTP; Hudson, Illinois) was used for a 2nd set of constant head configuration testing. The primary source water for the BWTP is surface water from Lake Central Illinois. If needed, the plant can draw surface water from Evergreen Lake. Lake Central Illinois was the only source water at the time of the sampling for these experiments. BWTP processes 11.5 MGD, approximately.

Approximating from the volume of water needed to finish the constant head experiments using Newmark tap water and the volume of water in a single 55-gallon drum, it was determined that close to 40 drums would be needed to process the Central Illinois water to the desired endpoint. Since four drums could be hauled per trip, 10 trips were needed to obtain the required volume of sample water. Since the water quality changes with time,

collecting raw water samples on different days creates a representative sample of the natural fluctuations of water quality. Sample water was collected between November 2013 and March 2014. Since the water sample was filter bed effluent collected prior to the final chlorination step, BWTP water was not dechlorinated (using sodium bisulfite) before RO processing.

4.1 Calculation of the Concentration Factor

An important parameter for assessing the retention of NOM and ionic species is the concentration factor (CF). The CF obtained was obtained with Equation 4.1:

$$CF = \left[\frac{X_{(t)}}{X_{(i)}}\right] \qquad \text{Equation 4.1}$$

Where $X_{(t)}$ is the value of a parameter (DOC, UVA_{254nm}, conductivity, chloride or sulfate) at any given time and $X_{(i)}$ is the initial value of that parameter. An initial sample of the decreasing volume operation using Newmark tap water was taken at the beginning of cycle 1. An initial sample of the constant head operation was taken from the process tank after quenching. The greatest source of inconsistency in the *CF* data comes from the initial values since the initial value is close to detection limit for some of the monitored parameters. If the initial value is not accurately determined, the calculated *CF* at any time will deviate from the true *CF* for the process tank water considerably.

For each setup, a water *CF* was used. For the decreasing volume,

$$CF = \frac{V_{tank} + V_P + V_C}{V_{tank} - V_C} \qquad \text{Equation 4.2}$$

Where V_{tank} is the filled volume of the tank (180 L), V_p is the total volume processed up to the end of the second to last cycle and V_c is the volume removed from the last cycle.

For the constant volume setup, the *CF* was determined as:

$$CF = \frac{V_{tank} + V_p}{V_{tank}} \quad \text{Equation 4.3}$$

Where V_p represents the total volume processed up to any time.

For the volume reduction phase, the *CF* was determined as:

$$CF = \frac{V_{tank} + V_p + V_c}{V_{tank} - V_c} \quad \text{Equation 4.4}$$

Where V_{tank} is the volume of water in the process tank when full (180 L), V_c is the volume of water removed during the volume reduction phase and V_p is the total volume removed through the constant volume phase. The *CF* values calculated based on water volumes (Equations 4.2 to 4,4) were compared to those calculated from initial and final on DOC concentraions, UVA_{254nm} measurements and conductivity (Equation 4.1) to assess the recovery rate.

4.2 Decreasing Volume Experiments Using Newmark Tap Water

The first set of experiment used the decreasing volume protocol to concentrate NOM. The experiment processed close to 1200 L (Figure 4.1) and was conducted for a total process time of 3000 minutes over 12 cycles. The decrease in water volume resulted in an increase in DOC (Figure 4.3), UVA_{254nm} (Figure 4.4) and conductivity (Figure 4.7) in each cycle while the permeate flow rate decreased.

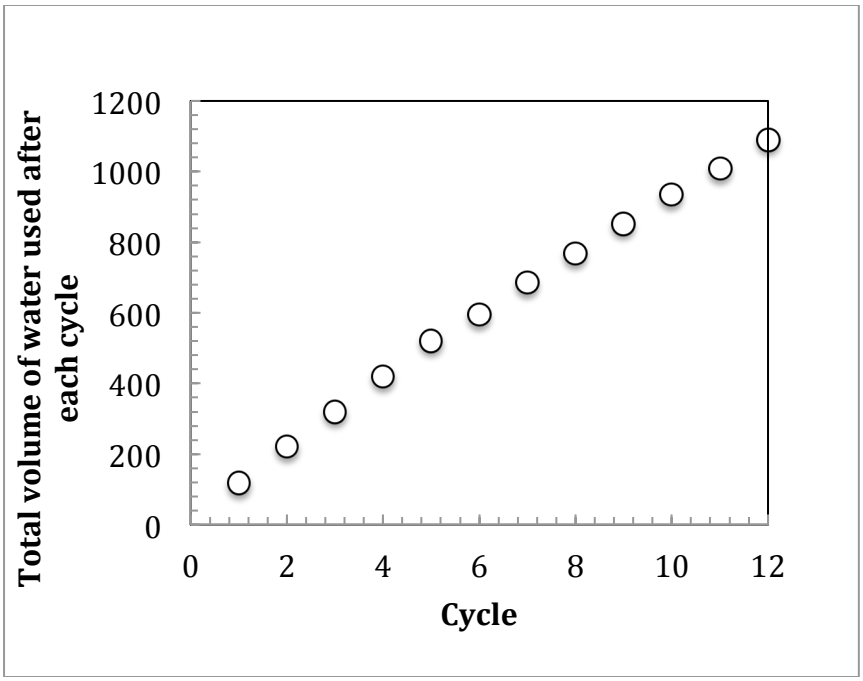

Figure 4.1: Volume of water processed throughout the decreasing volume experiment with Newmark tap water.

At the conclusion of each cycle, the water concentration factor was determined (Figure 4.2). The volume at the end of each cycle was not a constant value. The DOC data is consistent with the water concentration factors for cycles 1-4 (Figure 4.3). For cycles 5 through 12, the DOC values were approximately one-half of their expected value. This is attributed to loss of organic carbon during RO process or inaccuracy in the DOC analysis. On the other hand, the increase in UV absorbance at 254 nm agreed well with the water CF (Figure 4.4).

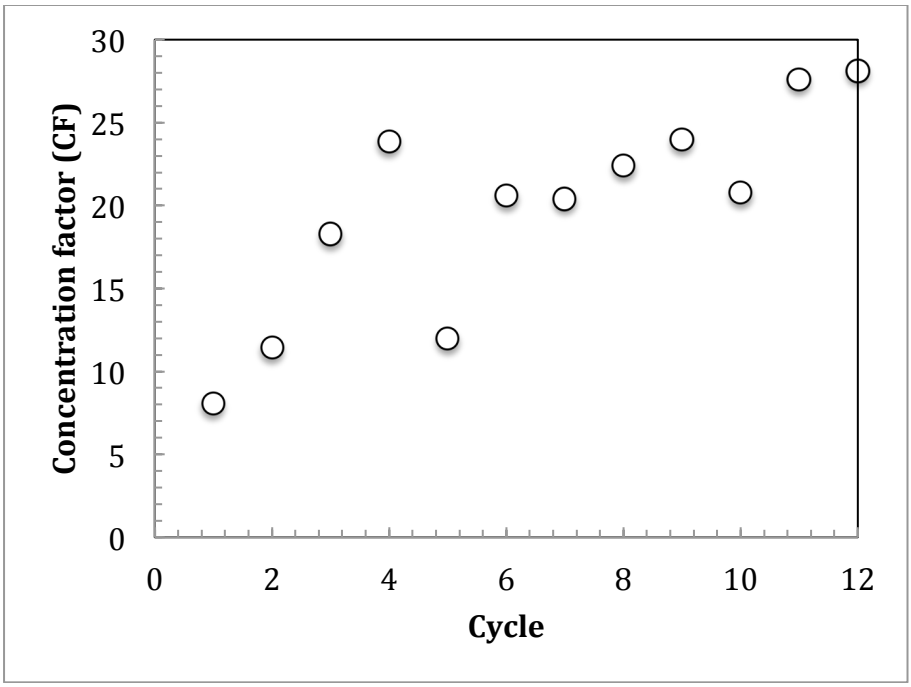

Figure 4.2: Water concentration factor at the end of each cycle of RO processing with Newmark tap water.

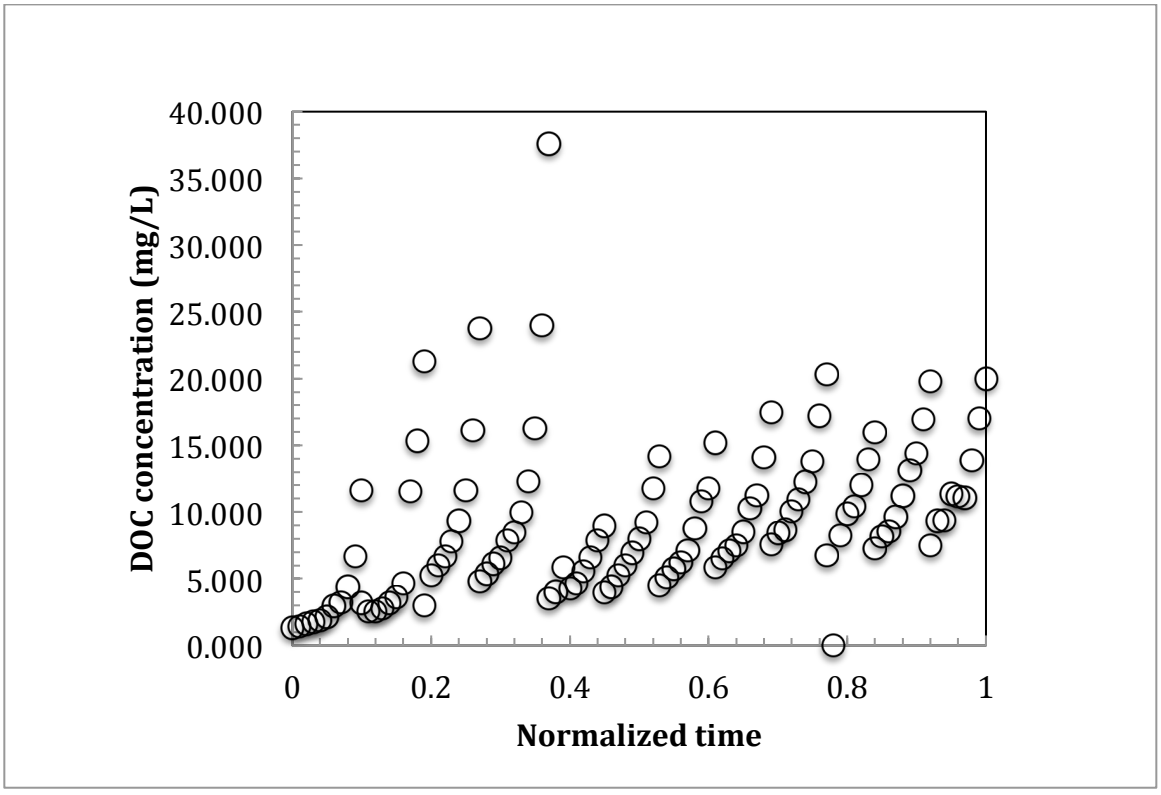

Figure 4.3: Change in DOC over time throughout 12 cycles of decreasing volume RO processing with Newmark tap water.

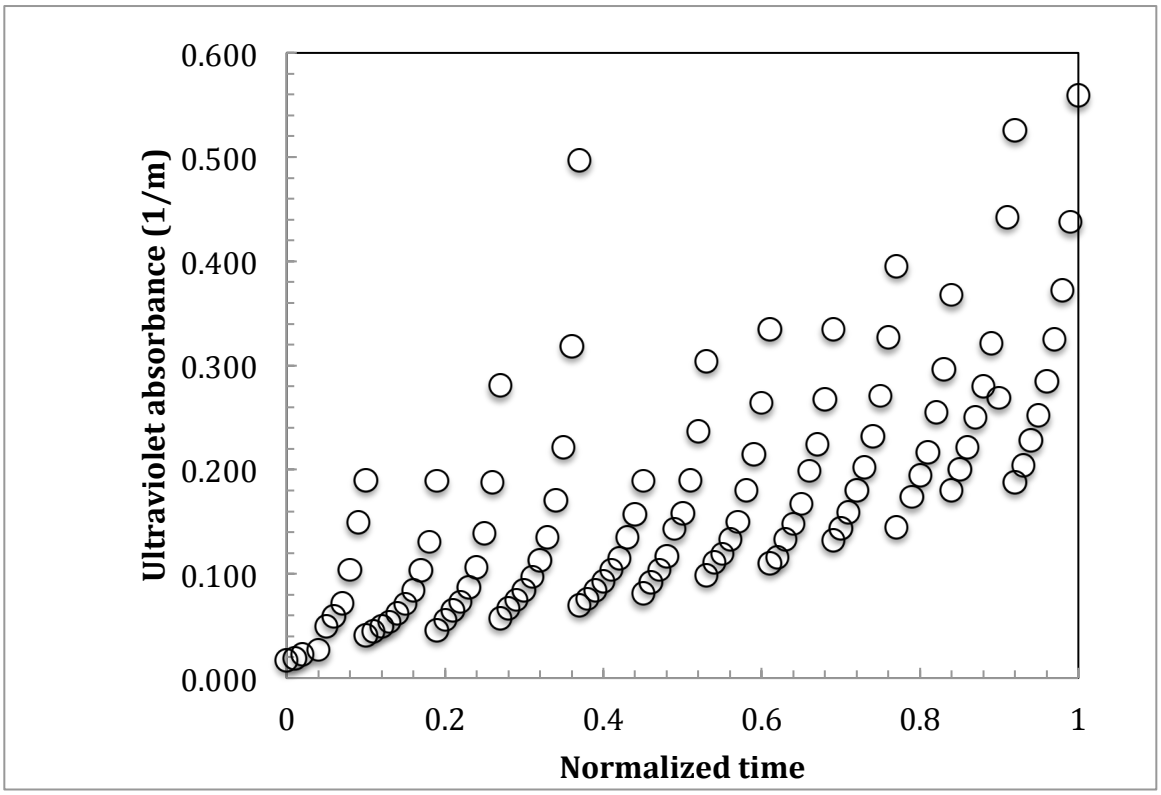

Figure 4.4: Change in UV absorbance (at 254 nm) over time throughout 12 cycles of decreasing volume RO processing with Newmark tap water.

Specific ultraviolet absorbance (SUVA) was calculated from UVA_{254nm} and DOC data to examine if the chemical characteristics of NOM were altered by RO process. The $SUVA_{254nm}$ data appears to show an increase over time. $SUVA_{254nm}$ is used as an indirect measure of the degree of aromaticity in NOM (Kitis et al., 2001) and the correlation with the aromatic carbon is established as:

$$\%\ aromatic\ carbon = 6.52 * (SUVA_{254nm}) + 3.63 \qquad \text{Equation 4.5}$$

The calculated aromatic carbon content shows nominal change over time (Figure 4.6). The nominal change in percent aromatic carbon affirms that the RO process did not significantly change the chemical characteristics of NOM.

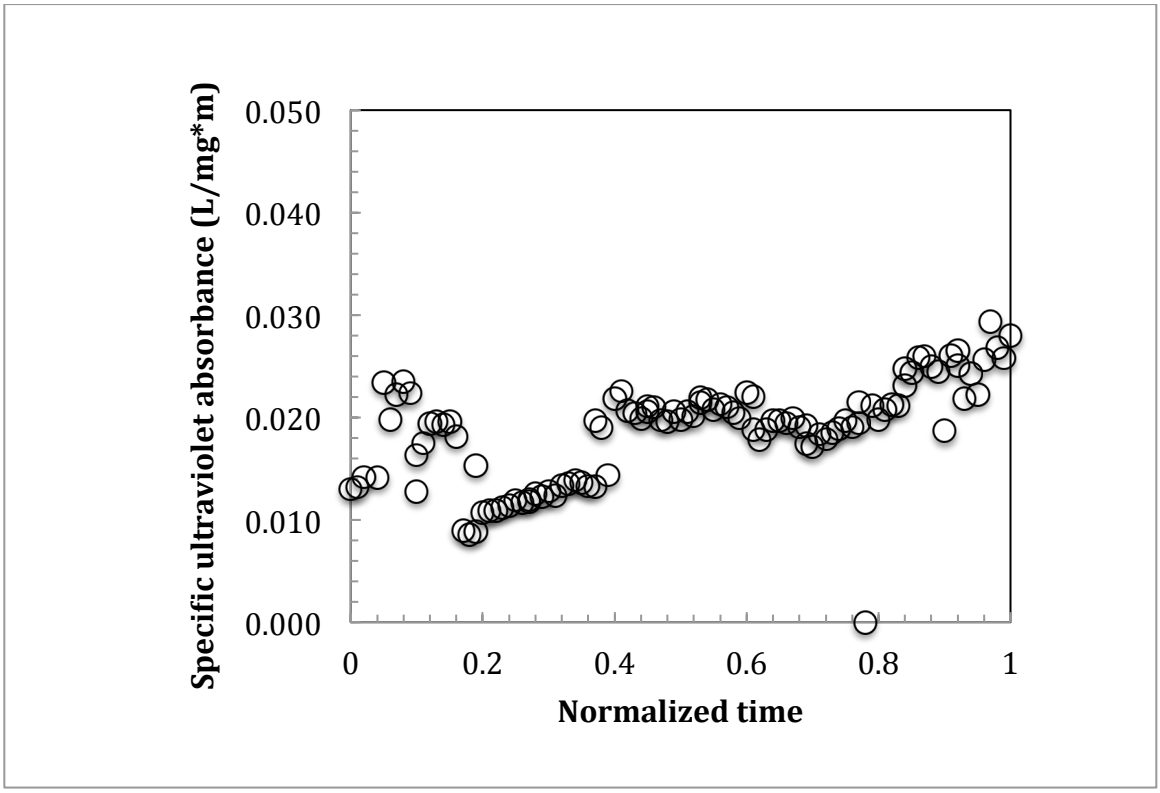

Figure 4.5: Change in SUVA $_{254nm}$ over time throughout 12 cycles of decreasing volume RO processing with Newmark tap water.

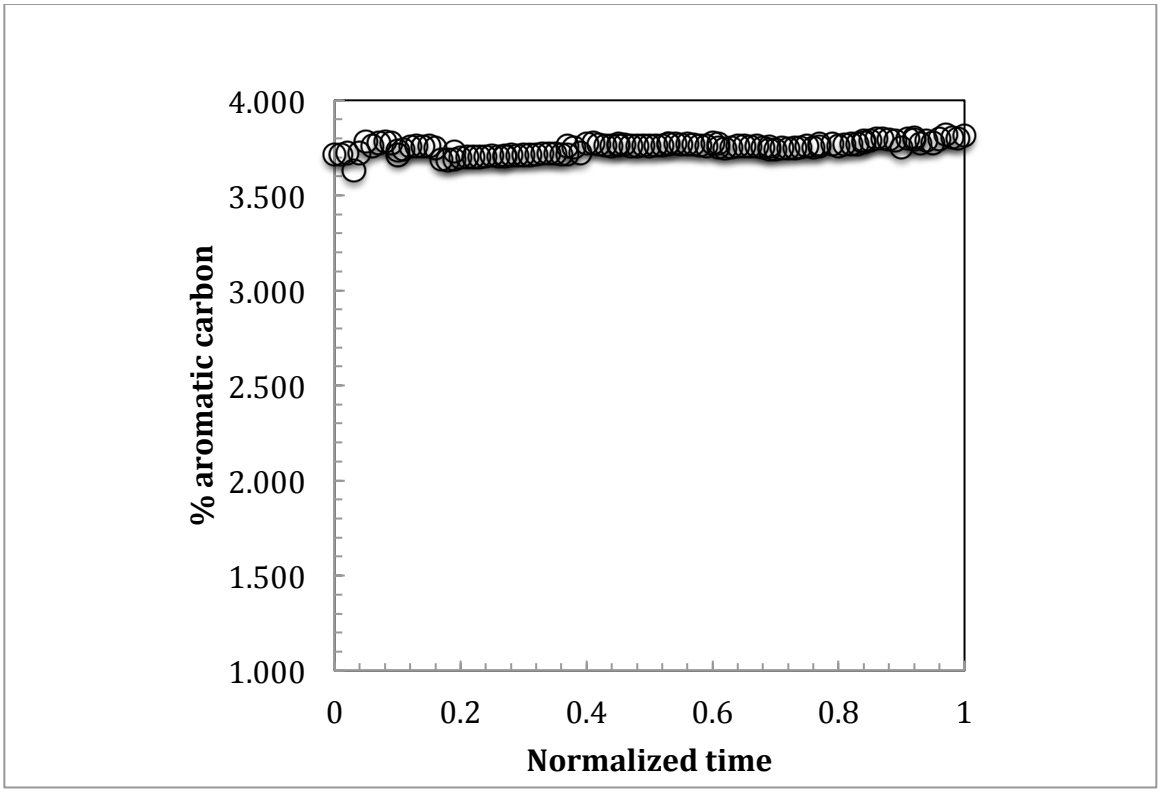

Figure 4.6: Change in percent aromatic carbon (from NOM) over time throughout 12 cycles of decreasing volume RO processing with Newmark tap water.

The *CF* values calculated from conductivity did not represent actual *CF* values accurately as a result of addition of quencher in the sample tank (Figure 4.7). Equation 4.6 shows the reaction of sodium bisulfite with the residual chlorine:

$$NaHSO_3 + H_2O + Cl_2 \rightarrow NaHSO_4 + 2HCl \qquad \text{Equation 4.6}$$

Two of the predominant anions, chloride and sulfate, present in Newmark tap water were analyzed using ion chromatography. The concentration of chloride increased at a faster rate than that of sulfate (data not shown), which agreed well with the stoichiometry of the quenching reaction in Equation 4.6, every mole of $NaHSO_3$ added produced one mole of SO_4^{2-} and two moles of Cl^-.

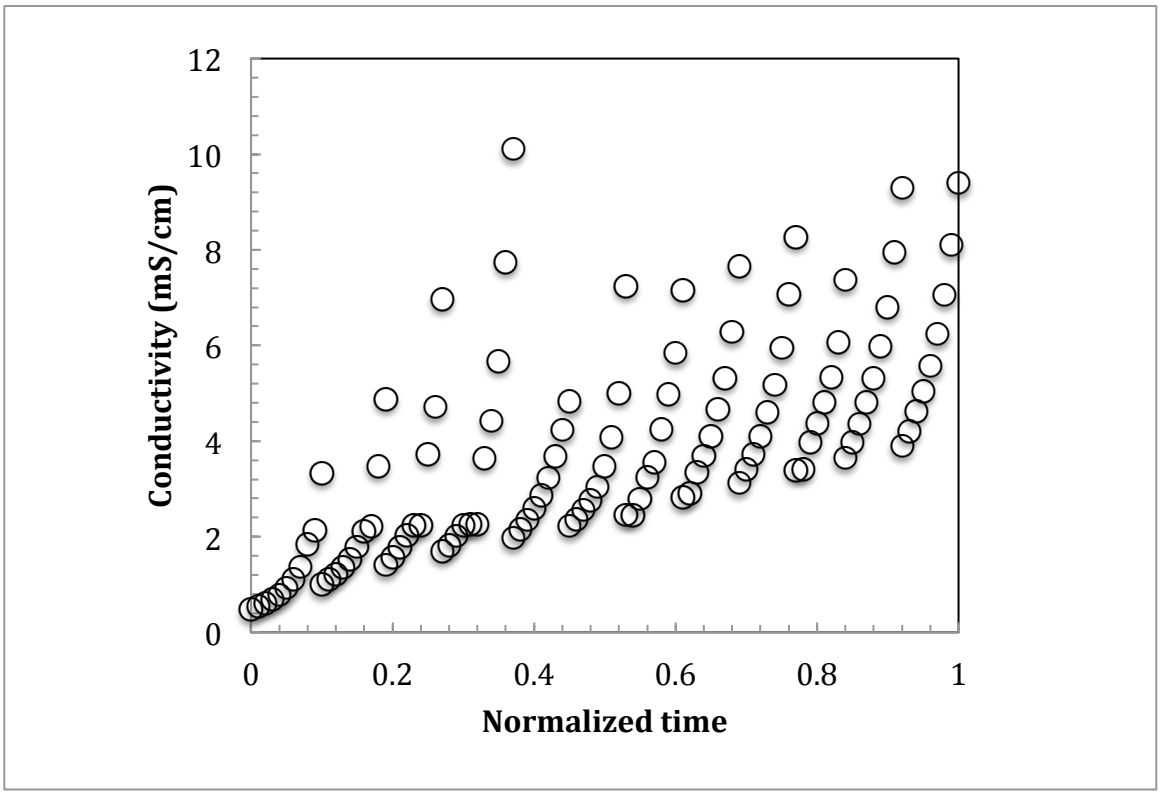

Figure 4.7: Change in conductivity over time throughout 12 cycles of decreasing volume RO processing with Newmark tap water.

4.3 Constant Volume Experiments

4.3.1 Constant Volume Phase for Processing of Newmark Tap Water

In the constant head experiments, the volume in the process tank was kept constant during the first part of the run. After a period of constant volume operation, the inflow of raw water was stopped, and the water volume in the process tank was reduced to further concentrate NOM. The moment to switch to the decreasing volume phase was decided from the concentration factor of the 180 L water sample, the desired final concentration factor and the concentration factor needed from the volume reduction phase.

The first phase of constant volume experiment using Newmark tap water lasted for 7000 minutes during which a total water volume of 5271 L was processed (Figure 4.8). At the end of the 7000 minutes, 5271 L of water was reduced to 180 L, resulting in the water *CF* of 29.3.

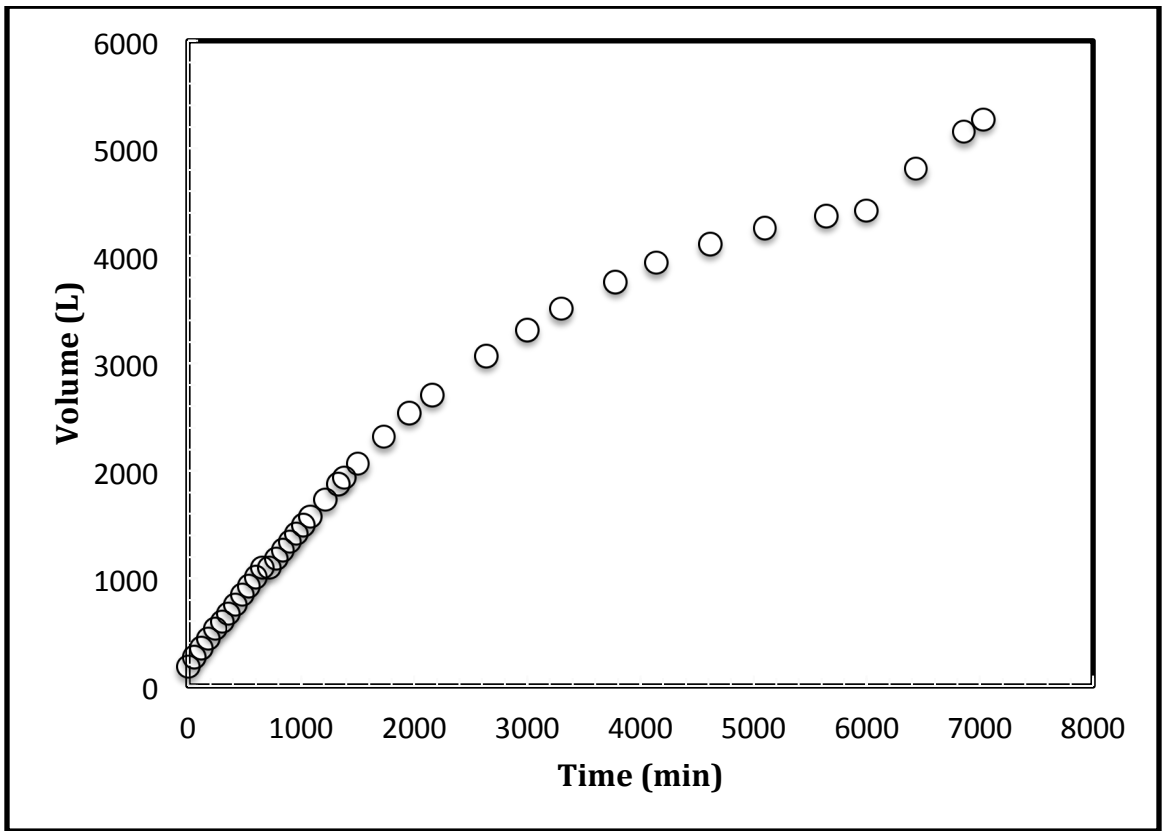

Figure 4.8: Increase in the volume of water processed during RO processing of Newmark tap water.

The accumulation of organic carbon mass is displayed in Figure 4.9. The *CF* for DOC was 33.5 at the end of the constant volume phase (Figure 4.9). Although the *CF* for DOC is comparable with the water volume *CF*, suggesting good retention, the DOC recovery was more than 100%. Since the calculated *CF* at any time depends on the initial value, the

higher than expected *CF* for DOC could originate from the initial value being lower than the average DOC value in Newmark tap water throughout the experiment. The DOC level for the initial sample was 1.01 mg/L. If the DOC analyzer gave an output of 1.16 mg/L, the *CF* for DOC would align with the water volume *CF*. Empirically, it is not unusual for the TOC analyzer to deviate ± 0.5 mg/L during analysis, but again it could be that the DOC concentration in Newmark tap water might have increased over time.

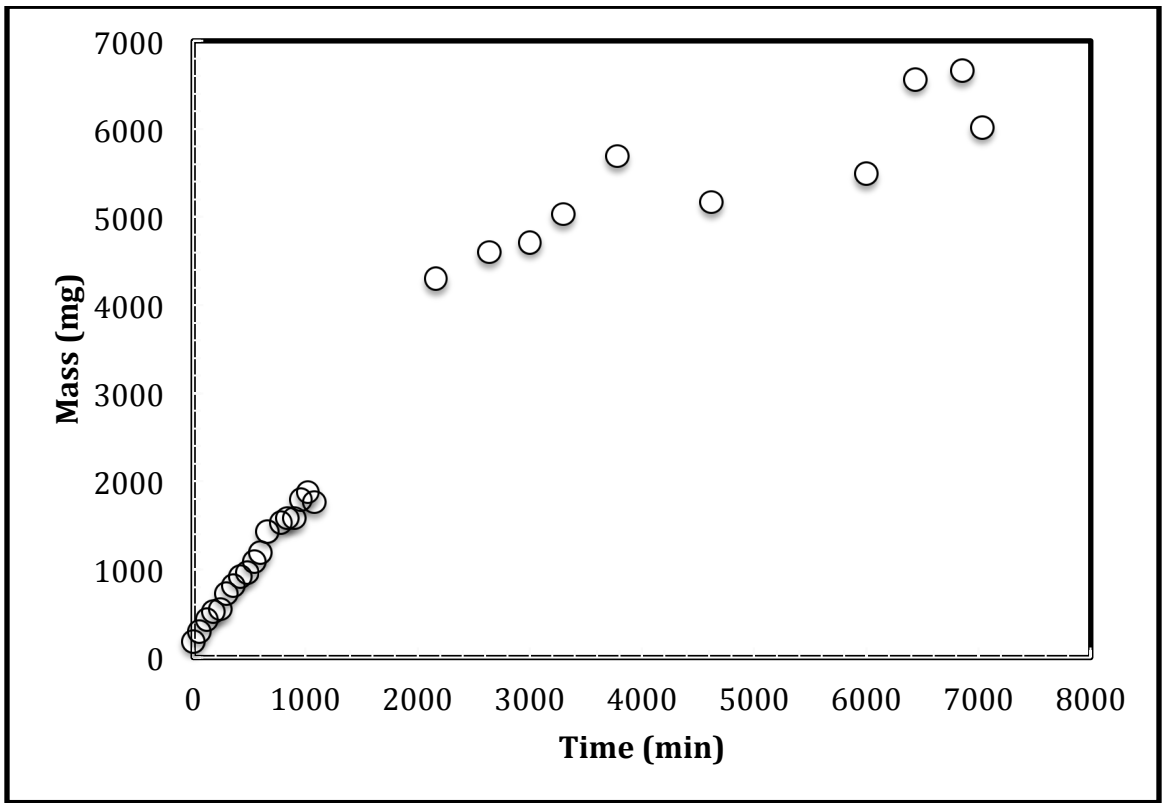

Figure 4.9: Increase in the mass of organic carbon over time during RO processing of Newmark tap water.

The *CF* for UVA_{254nm} at the end of the constant volume phase was 14.6 (Figure 4.10). This value is close to one-half the *CF* for the process tank water sample. Since the UVA_{254nm} of the initial sample was close to the lower limit of detection for the spectrophotometer, the

value might not be very accurate. Figure 4.11 shows that the $SUVA_{254nm}$ fluctuated for the first 300 minutes of process time. After 300 minutes, the values of $SUVA_{254nm}$ were stable. With both DOC and UVA_{254nm} close to the detection limit, accurate determination of $SUVA_{254nm}$ was difficult at the early stage. The slight downward trend of the data is considered negligible. UVA_{254nm} data points at 6435 and 6855 minutes were considered outliers due to experimental error. They were approximately one-half of their expected values.

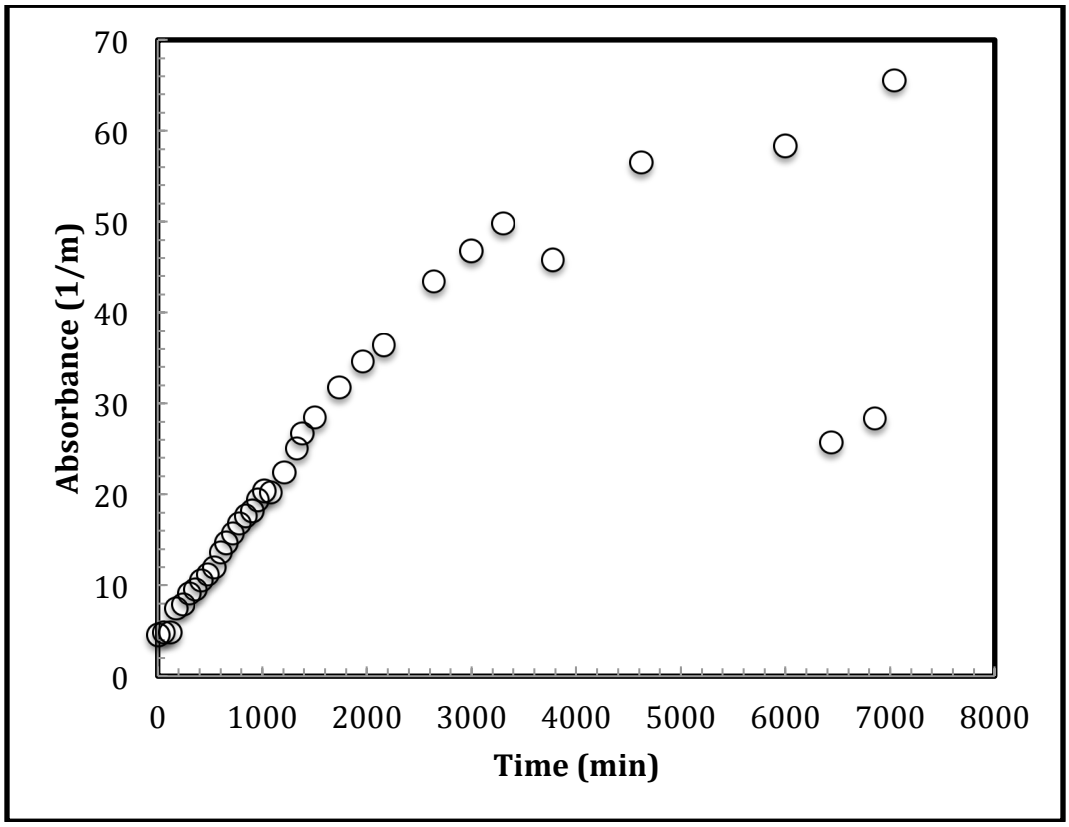

Figure 4.10: Increase in UVA at 254 nm throughout RO processing of Newmark tap water.

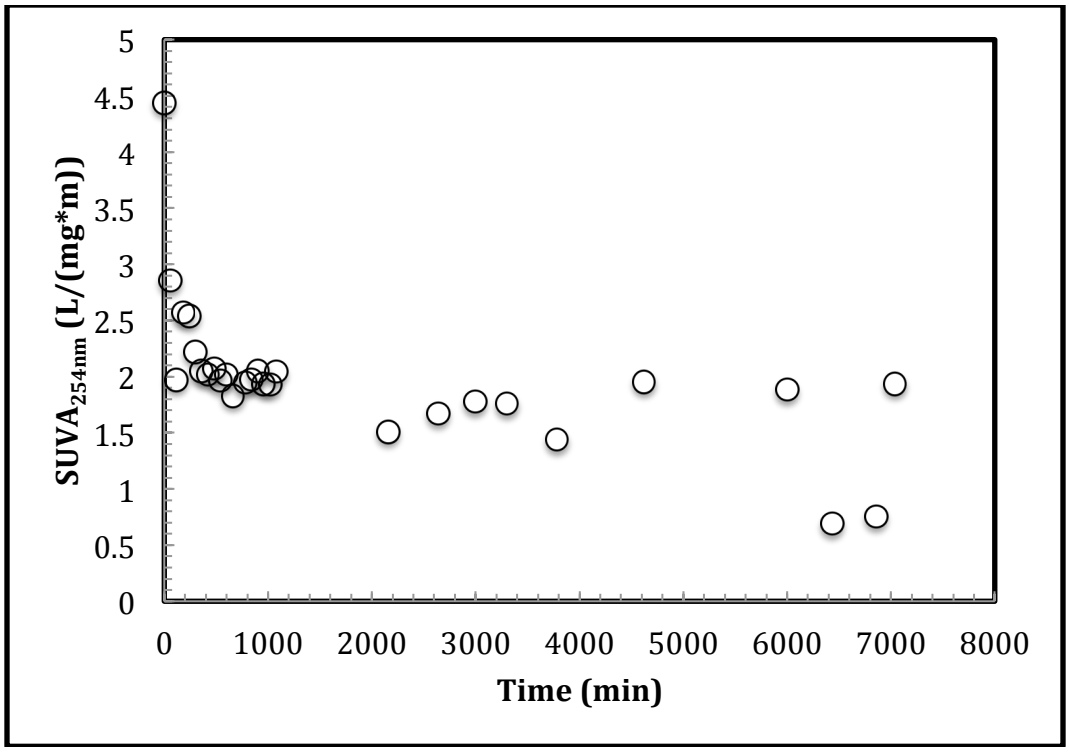

Figure 4.11: Change in $SUVA_{254nm}$ throughout RO processing of Newmark tap water.

The *CF* for the conductivity was 47.6 at the end of the constant head operation phase (Figure 4.12). It needs to be mentioned again that this *CF* value does not represent the true conductivity *CF* due to quencher addition discussed earlier. At the end of 7000 minutes of process time, the conductivity was 11.89 mS/cm. This level of conductivity was still not enough to prevent significant loss of NOM during ED process (Gurtler et al., 2008). At this point, the volume reduction phase was implemented. ED processing began after the volume reduction phase.

The values for conductivity from 2640 to 6000 minutes remained relatively unchanged. For the first 6000 minutes, the conductivity data were collected using the conductivity cell fixed onto the process tank, which had been set at the measuring range of up to 1999 µS/cm. Data were reliable only until around 5 mS/cm and thus the conductivity data

between 2640 and 6000 minutes are not represented accurately. The conductivity probe was replaced with a unit that had a cell constant of 10. At t = 6435 minutes and thereafter, the samples were diluted to be within an appropriate measuring range and analyzed using the new probe.

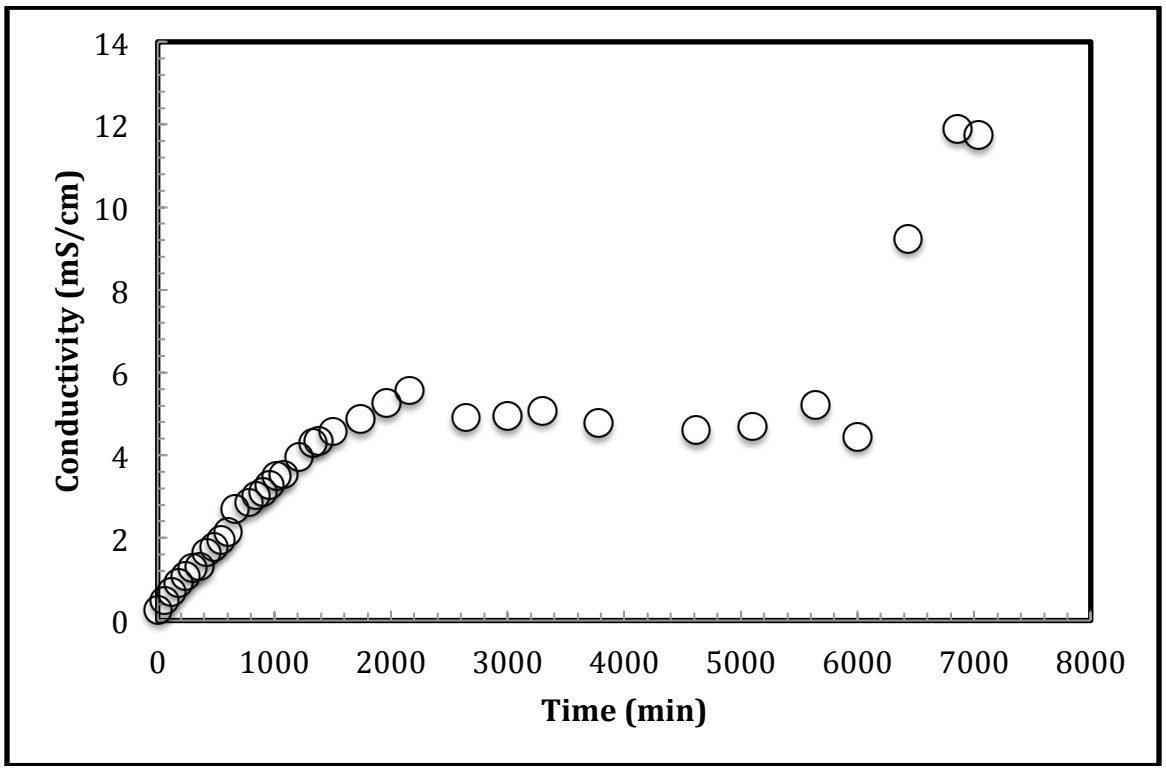

Figure 4.12: Increase in conductivity over time during RO processing of Newmark tap water.

4.3.2 Volume Reduction of Reverse Osmosis processed Newmark Sample Water

After 7035 minutes of operation, the flow of raw water into the process tank was stopped, and the water volume was further reduced to 87 L in 180 minutes. After the volume reduction phase, the final concentration of DOC was 186.6 mg/L (Figure 4.13), UVA_{254nm}

increased to 2.96 (1/cm) (Figure 4.14) and the conductivity reached 63 mS/cm (Figure 4.15). During the volume reduction phase, the *CF* for UVA_{254nm} and conductivity correlated well and both achieved 5 times concentration. The *CF* for DOC during the volume reduction phase was closer to 4 times.

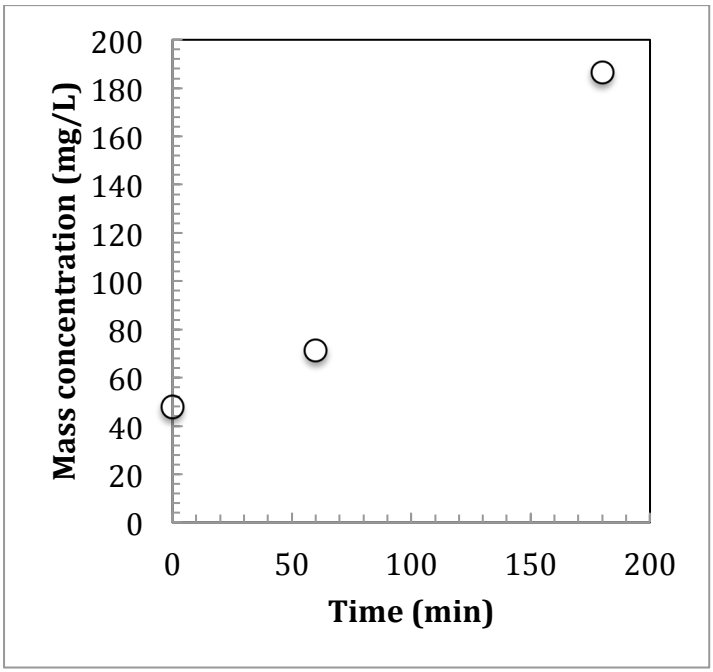

Figure 4.13: Increase in DOC concentration during volume reduction phase of constant volume experiment with Newmark tap water.

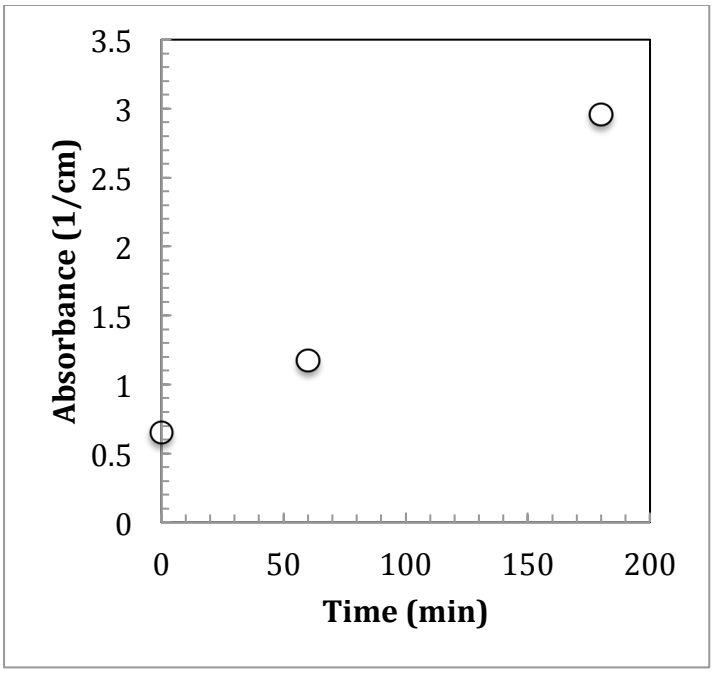

Figure 4.14: Increase in UV absorbance at 254 nm during volume reduction phase of constant volume experiment with Newmark tap water.

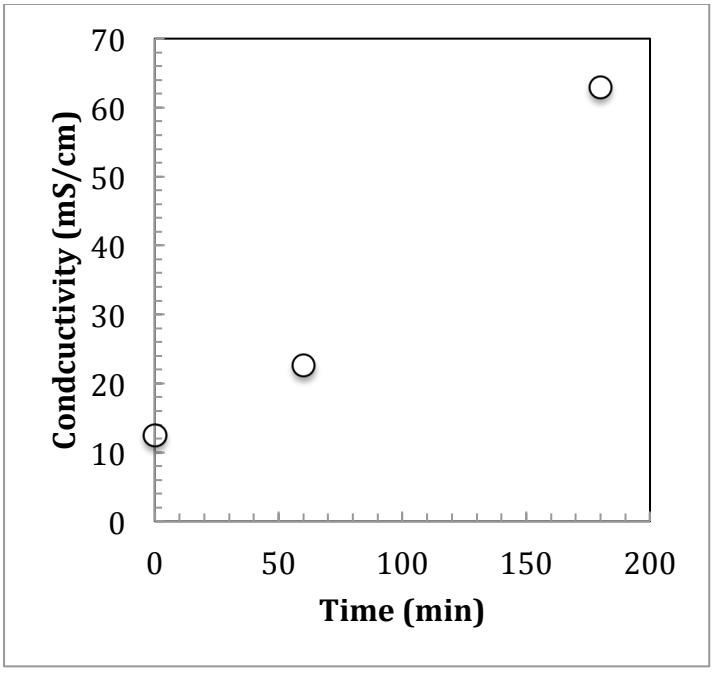

Figure 4.15: Increase in conductivity during volume reduction phase of constant volume experiment with Newmark tap water.

4.3.3 Overall Results for Constant Volume and Volume Reduction Data Combined for Newmark Tap Water

Figures 4.16 – 4.18 show the increase of DOC, conductivity and UVA_{254nm} over the constant volume and volume reduction phases. The concentration factors at each phase are summated in Table 4.1. In total, 5271 L of water were processed with the RO unit while the volume in the process tank was kept constant at 180 L (constant volume phase) and this 180 L was reduced down to 87 L.

Table 4.1: Summary of the experiments using Newmark tap water and the constant volume/volume reduction protocol.

Parameter	**Initial value (CF)**	**Final value after constant volume phase (CF)**	**Final value after volume reduction phase(CF)**
Process time (min)	-	7035	7215
Volume of water processed (L)	-	5271→180 (29.3x)	5271 → 87.0 (60.6x)
DOC (mg/L)	1.014	33.93 (33.5x)	186.6 (184x)
UVA (1/m)	4.5	65.6 (14.5x)	296 (65.7x)
Conductivity (mS/cm)	0.25	11.74 (46.96x)	63 (252x)

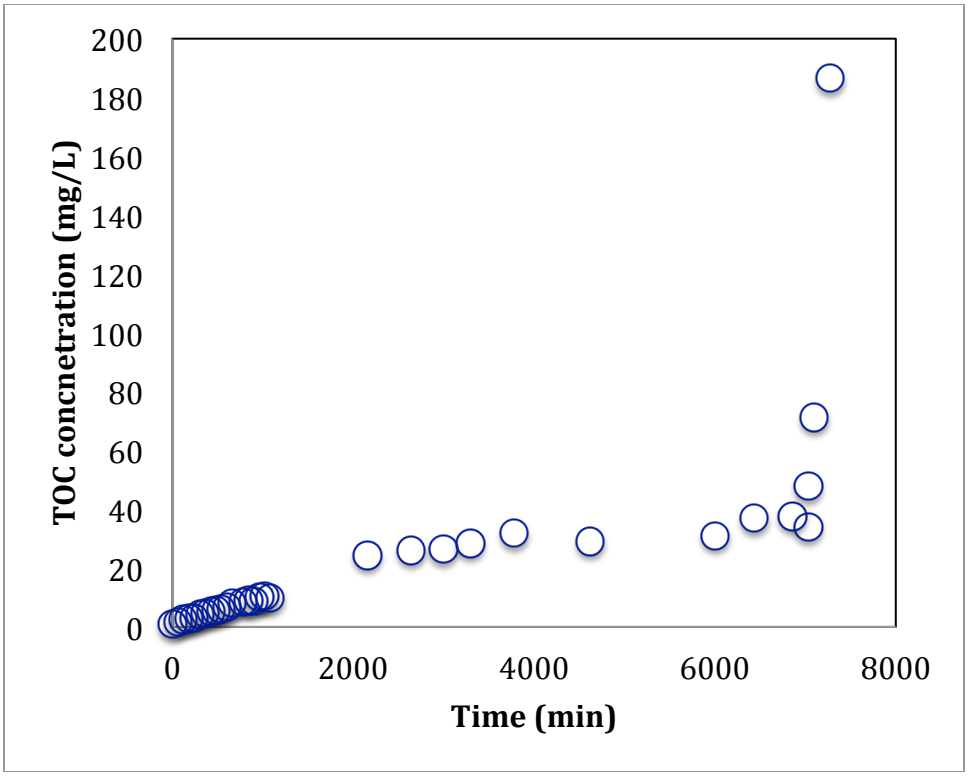

Figure 4.16: Increase in DOC concentration throughout constant head and volume reduction phases of experiment with Newmark tap water.

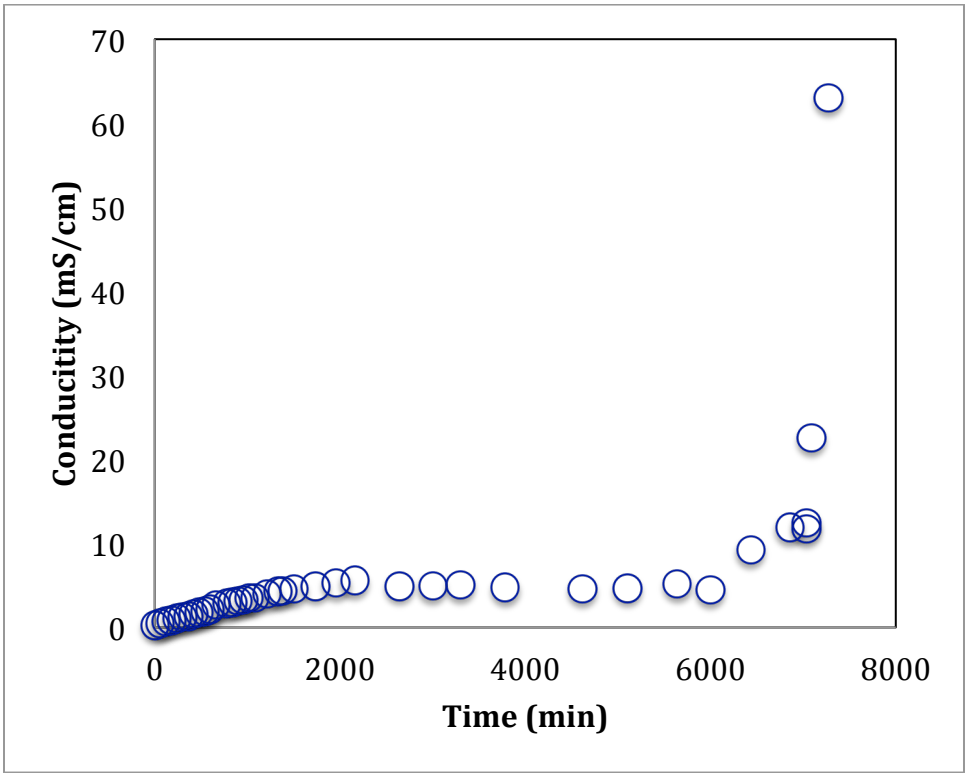

Figure 4.17: Increase in conductivity throughout constant head and volume reduction phases of experiment with Newmark tap water.

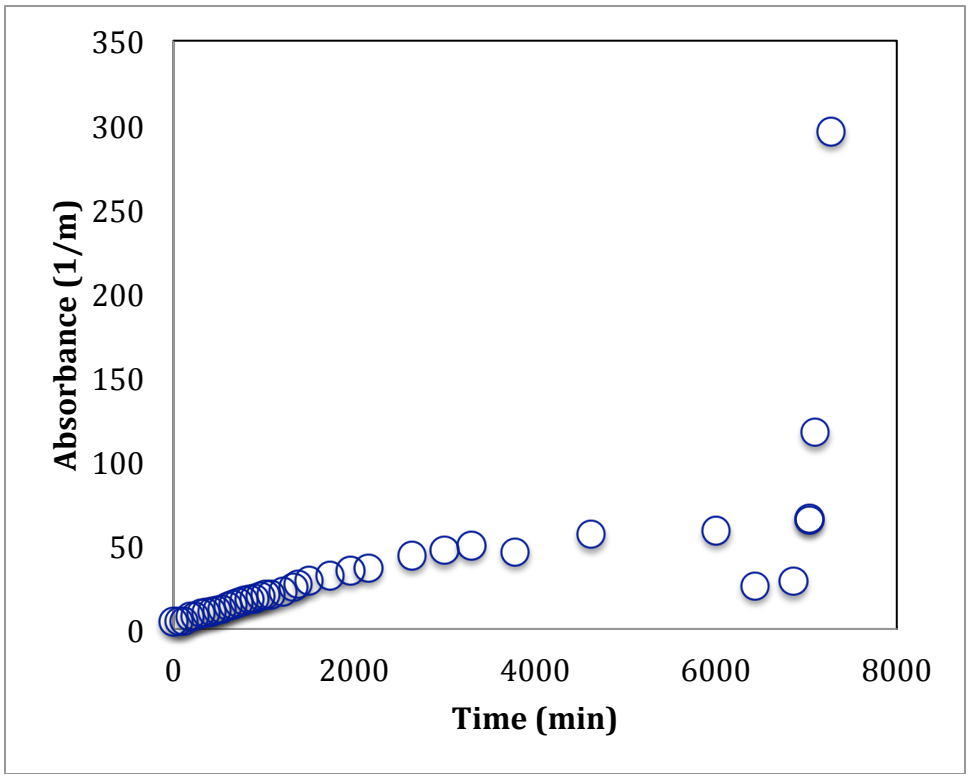

Figure 4.18: Increase in UV_{254nm} absorbance throughout constant head and volume reduction phases of experiment with Newmark tap water.

4.4 Constant Head Experiments Using Central Illinois Water

4.4.1 Constant Volume Phase with Central Illinois Water

As with Newmark tap water, constant volume operation was used to concentrate the Central Illinois water. The constant volume phase processed 4971 L in 6614 minutes while keeping the volume of water in the process tank constant at 180 L. The *CF* values calculated from water volume, DOC,UVA_{254nm} and conductivity were 27.8, 39.7, 36.2 and 30.3, respectively (Figures 4.19 – 4.22). Between the last two data points, the tube connecting the ion exchange column to the microfiltration setup gained high pressure and burst. At that time, the process water drained, by gravity, onto the lab floor. The last data

point represents a loss of approximately 2/3 the process water and an accidental volume reduction phase.

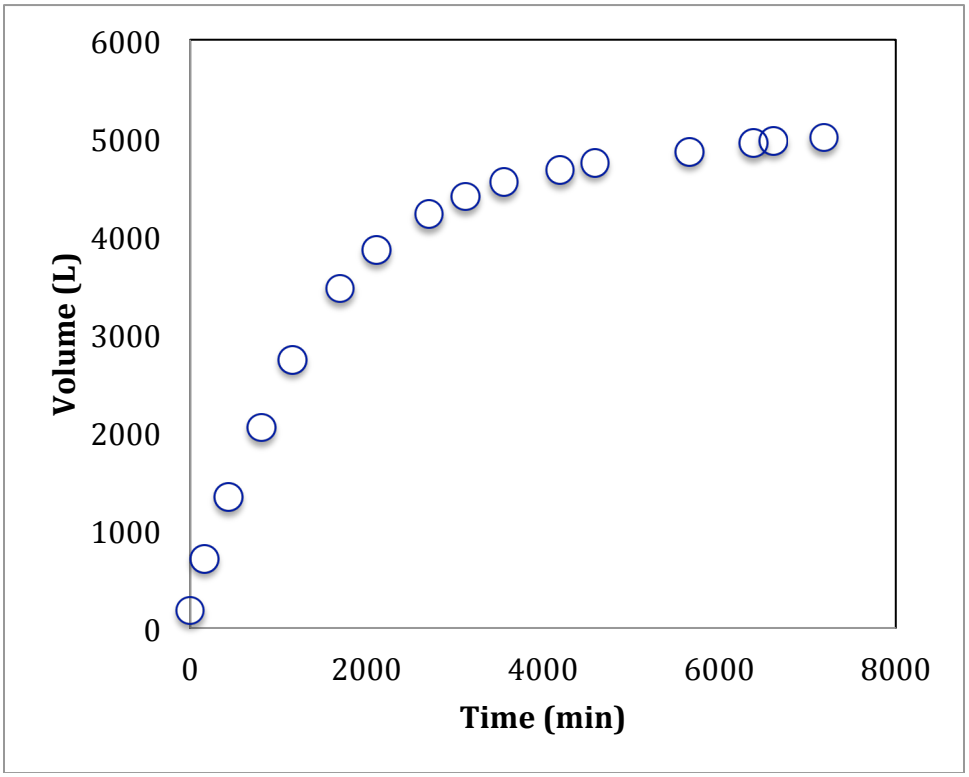

Figure 4.19: Increase in volume of water processed throughout constant volume phase of experiment with Central Illinois water.

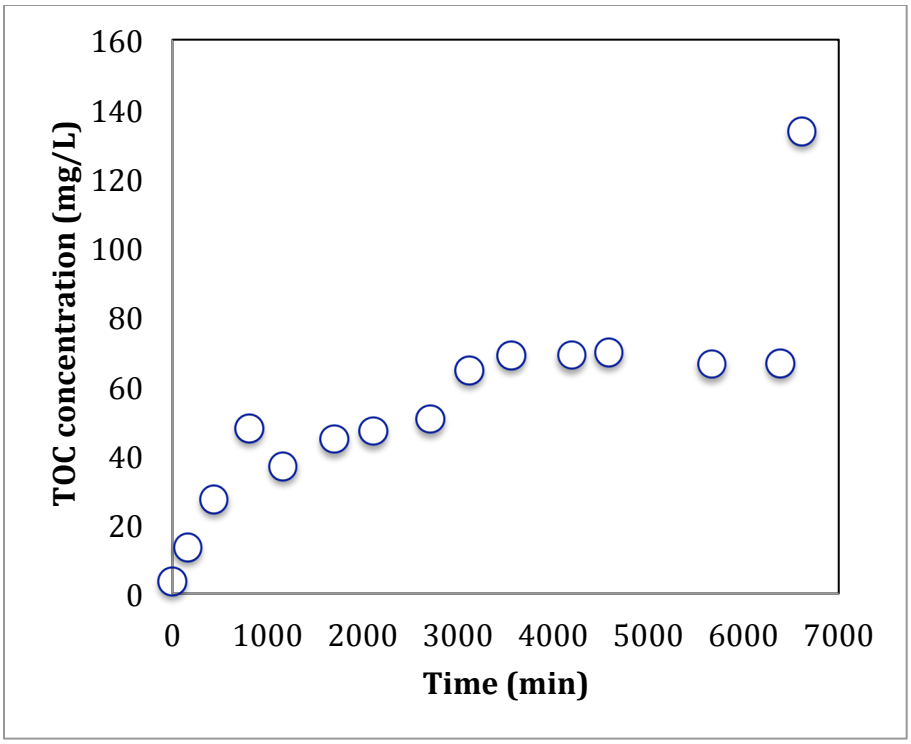

Figure 4.20: Increase in DOC throughout constant volume phase of experiment with Central Illinois water.

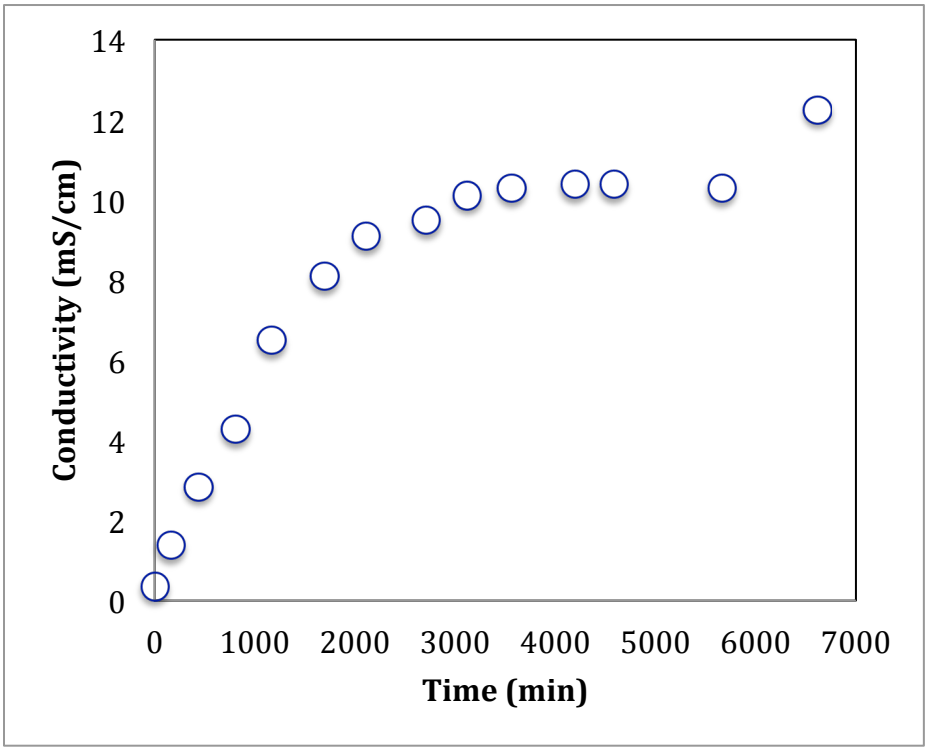

Figure 4.21: Increase in conductivity throughout constant volume phase of experiment with Central Illinois water.

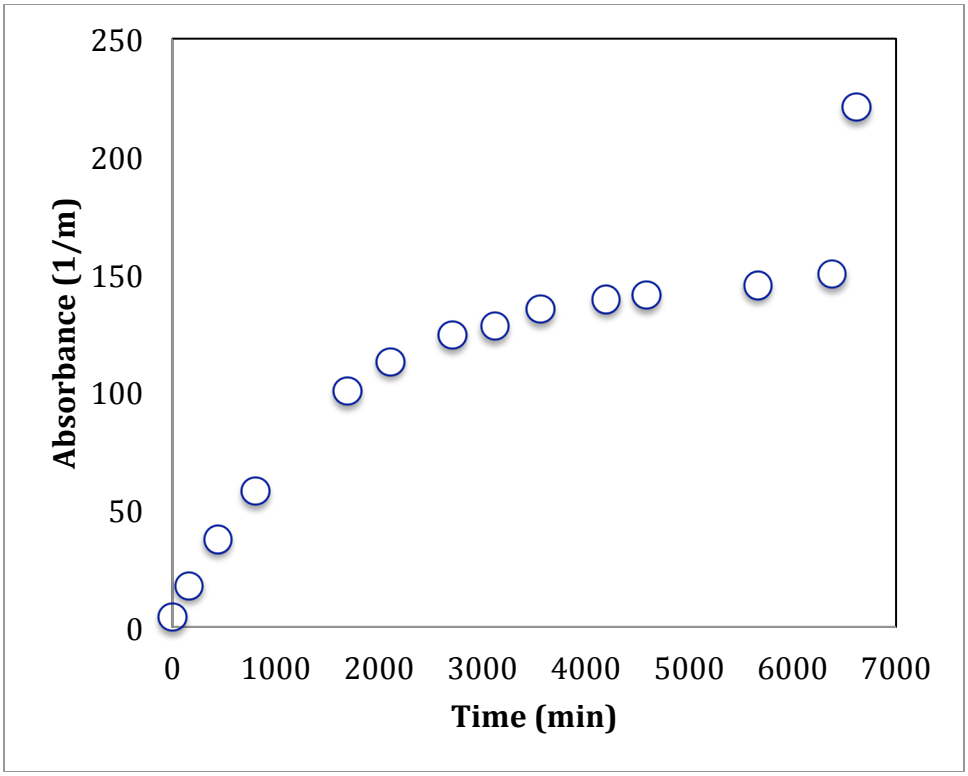

Figure 4.22: Increase in UV_{254nm} absorbance throughout constant volume phase of experiment with Central Illinois water.

Table 4.2: Final values for constant volume phase processing of Central Illinois water.

Parameter	**Final values after constant volume phase (*CF*)**
Processing time (min)	6614
Volume of water processed (L)	4971 (27.8x)
DOC concentration (mg/L)	66.4 (39.7x)
UVA_{254nm} (m^{-1})	150 (36.2x)
Conductivity (mS/cm)	10.3 (30.3)

4.4.2 Constant Volume Plus Volume Reduction for Central Illinois Water

After 6614 minutes of constant volume processing, about 140 L of water in the process tanks was lost by an accident. With the remaining ~40 L of concentrated water, the volume reduction phase was implemented. The volume reduction phase lasted for 573 minutes and 34 L of water was removed as permeate, resulting the final water volume of ~1 L. The final volume was slightly larger than the dead volume of the RO system. At the end of the volume reduction phase, the *CF* values for DOC, UVA_{254nm} and conductivity were 309.3, 775.6 and 441, respectively. Concentration data for these parameters are found in Figures 4.23 – 4.25. Due to the accidental sample loss, accurate determination of water concentration factor was difficult. The decline of permeate flux was observed as the water was concentrated (Figure 4.26). $SUVA_{254nm}$ ranged from 1.22 L/mg*m to 2.46 L/mg*m throughout processing. When converted to percent aromatic carbon, this change in $SUVA_{254nm}$ is considered negligible.

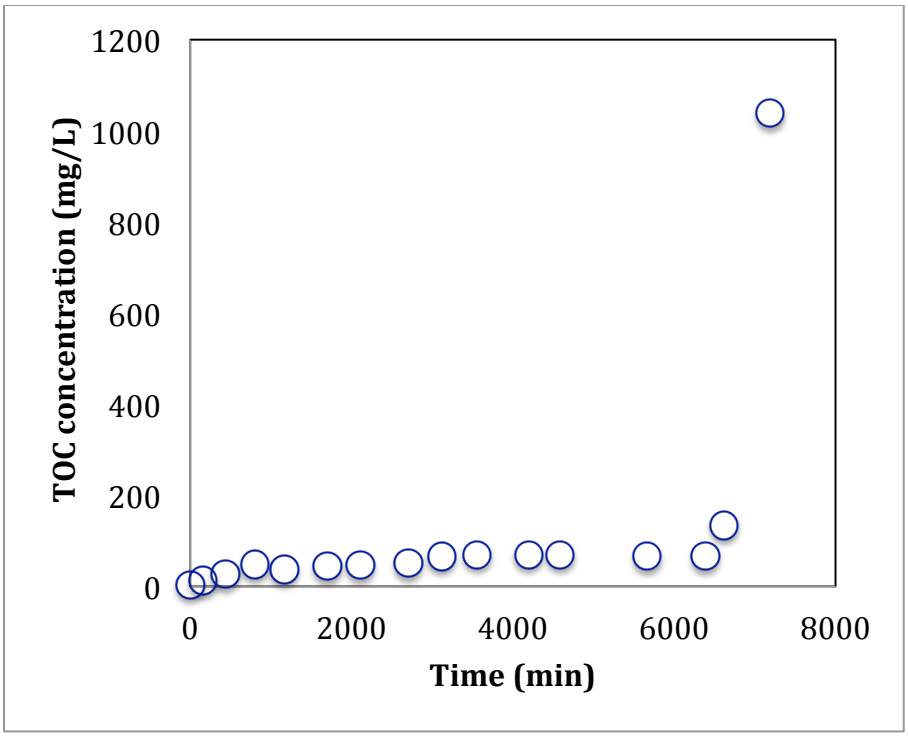

Figure 4.23: Increase in DOC throughout constant head and volume reduction phases of experiment with Central Illinois water.

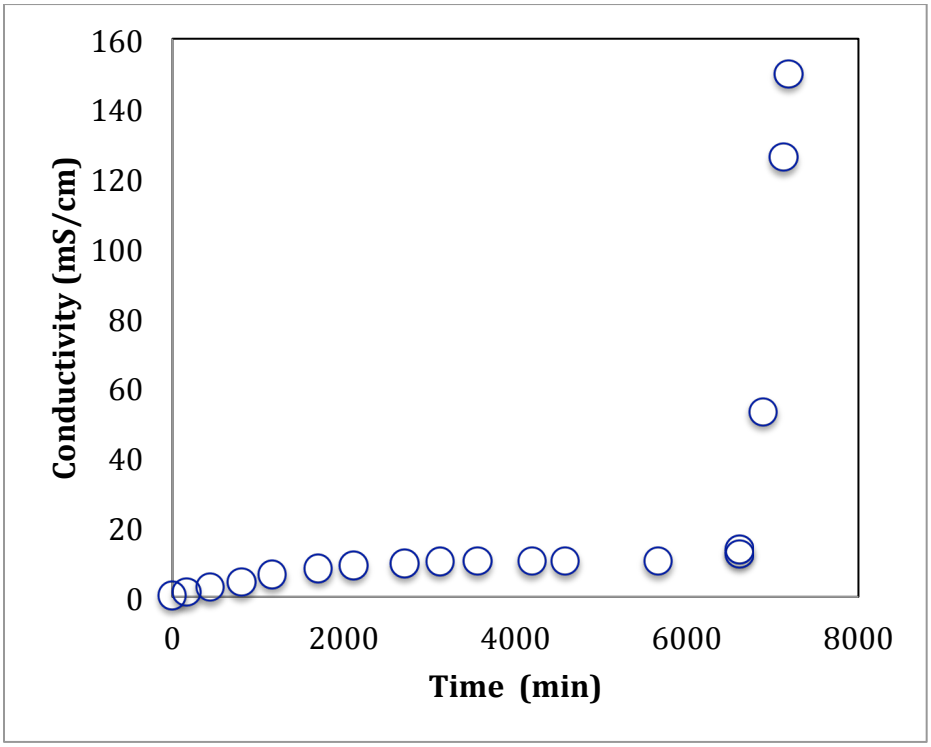

Figure 4.24: Increase in conductivity throughout constant head and volume reduction phases of experiment with Central Illinois water.

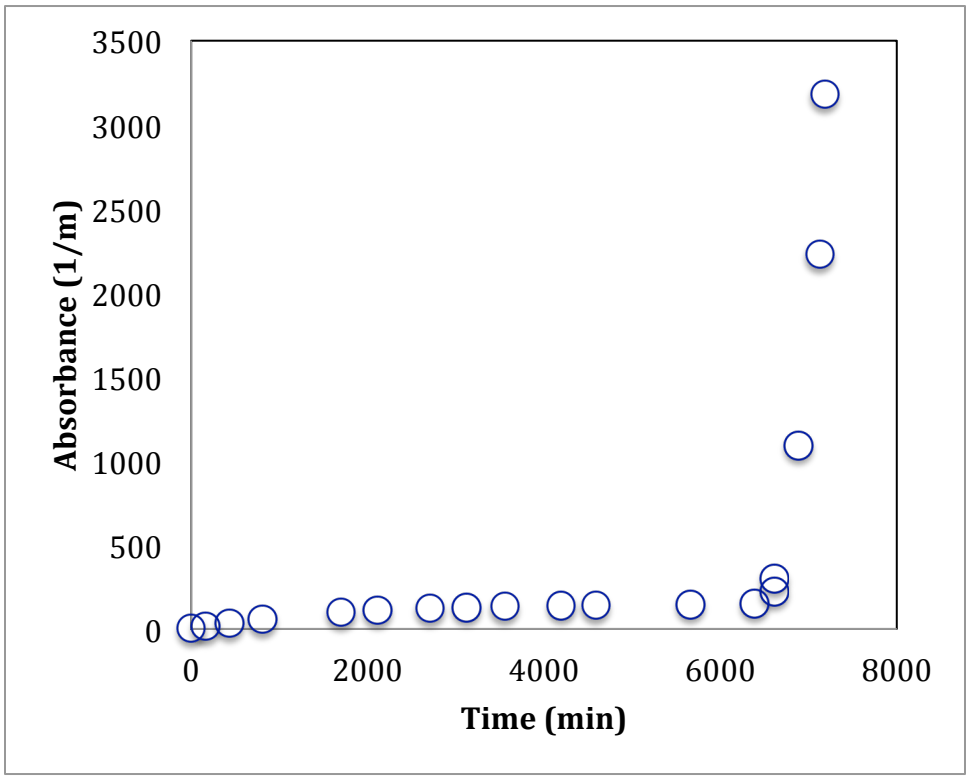

Figure 4.25: Increase in UV_{254nm} absorbance throughout constant head and decreasing volume phases of experiment with Central Illinois water.

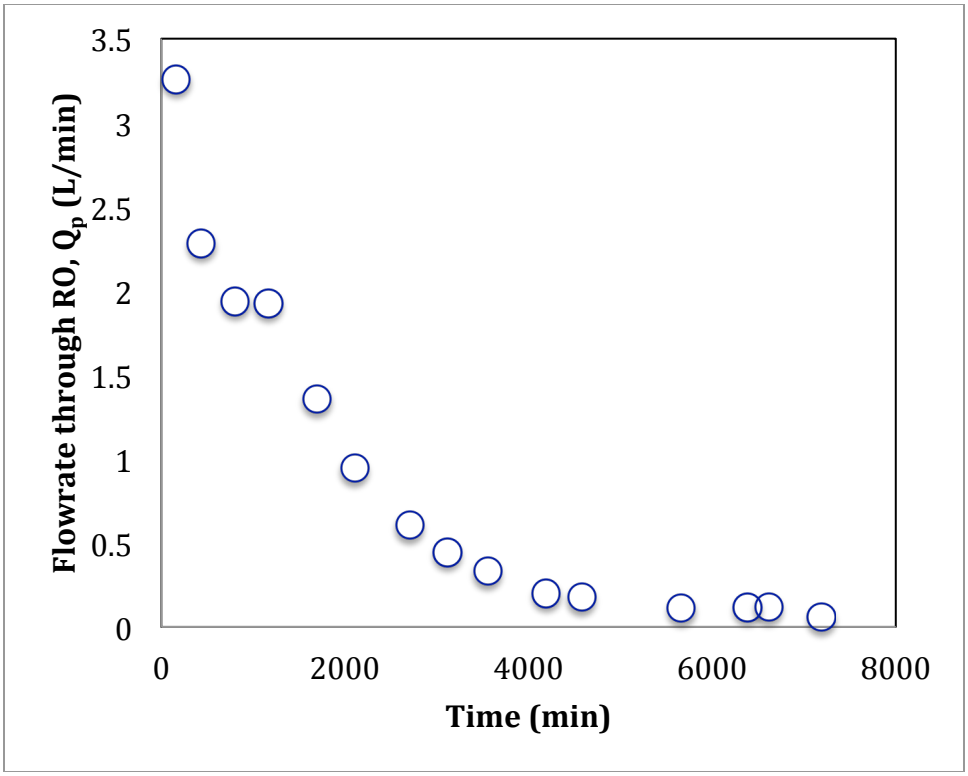

Figure 4.26: Decrease in permeate flowrate throughout constant head and decreasing volume phases of experiment with Central Illinois water.

4.5 Overview of RO Results

Table 4.3 compares the volume of water processed, and the initial to the final values for DOC, conductivity and UVA_{254nm}. When comparing the decreasing volume operation and the constant head operation at the end of the constant volume phase, all setups reached a CF for water close to 30. However, the constant volume setups achieved this water CF with 180 L while the decreasing volume setup ended with 39 L.

Table 4.3: Comparison of final values from the three processing setups. DV = decreasing volume ; CV = constant volume; VR = volume reduction.

Parameter	**DV w/ Newmark tap water (CF)**	**CV+VR w/ Newmark tap water (CF)**		**CV+VR w/ BWTP sample (CF)**	
		CV phase	**VR phase**	**CV phase**	**VR phase**
Process time (min)	3000	7035	7275?	6614	7187
Overall volume of water processed (L)	1089 → 39.0 (27.9x)	5271 → 180 (29.3x)	180 → 87.0 (60.6x)	4971 → 180 (27.8x)	Additional 34 L was removed**
DOC (mg/L)	1.311 → 19.98 (15.2x)	1.01 → 33.93 (33.5x)	33.93 →186.6 (184x)	3.35 → 66.4 (19.8x)	66.4 → 1036 (309.3x)
Conductivity (mS/cm)	0.48 → 9.4 (19.6x)*	0.25 → 11.74 (46.96x)*	11.74 → 63 (252x)*	0.34 → 10.3 (30.3x)	10.3 → 150 (441x)
UVA_{254nm} (1/m)	1.7 → 55.9 (32.9x)	4.5 → 65.6 (14.5x)	65.6 → 296 (65.7x)	4.1 → 150 (36.2x)	150 → 3180 (776x)

*Quencher addition contributes to the increase of conductivity
**Accurate determination of water *CF* was not possible due to the accidental loss of sample.

Overall flow rates were calculated using the overall water volume processed and the volume remaining. The overall flow rates for the decreasing volume operation with Newmark water, and overall constant volume operation with Newmark and Central Illinois water were 0.363 L/min, 0.713 L/min and 0.671 L/min, respectively. The decreasing volume setup had a flow rate approximately one-half of either constant volume setup. This was due to a higher increase in osmotic pressure over time from the cycling of volume reduction. The volumetric flow rate across RO membranes is described from Equation 2.2.

$$Q_p = SA(\Delta P - \Delta\pi) \qquad \text{Equation 2.2}$$

Since the constant volume operation experienced a sharp increase in conductivity only during the volume reduction phase, it was concluded that the constant volume operation was a more efficient NOM concentration method.

Between the two experiments using the constant volume setups, the difference in the overall flow rate with Newmark water and Central Illinois water can be attributed to the different water quality. The water from Central Illinois contained a DOC concentration of roughly three times that of Newmark water (1.01 mg/L vs. 3.35 mg/L).

For the decreasing volume experiment using Newmark water, the *CF* values from volume of water processed and UVA_{254nm} correlate well. The *CF* value for DOC was one-half of the water *CF*. For the constant volume plus volume reduction using Newmark water, the water *CF* and UVA_{254nm} agreed well. The *CF* value for DOC was three times the *CF* value for the processed water. For the constant volume plus volume reduction of the Central Illinois water sample, the *CF* for UVA_{254nm} was 2.5 times the *CF* value for DOC.

4.6 Electrodialysis

4.6.1 Preliminary Processing Concentrated Newmark Water

Upon completion of the constant volume RO processing of Newmark water, ED was investigated to desalt the sample. The initial conductivity and DOC concentration of the Newmark water sample were 11.74 mS/cm and 33.93 mg/L, respectively. ED was operated in constant voltage mode using 2 VDC and 3 VDC. The stack contained five cell pairs. Removal of salt species in this preliminary attempt was negligible (Figure 4.27). Lack of performance was investigated using NaCl solutions.

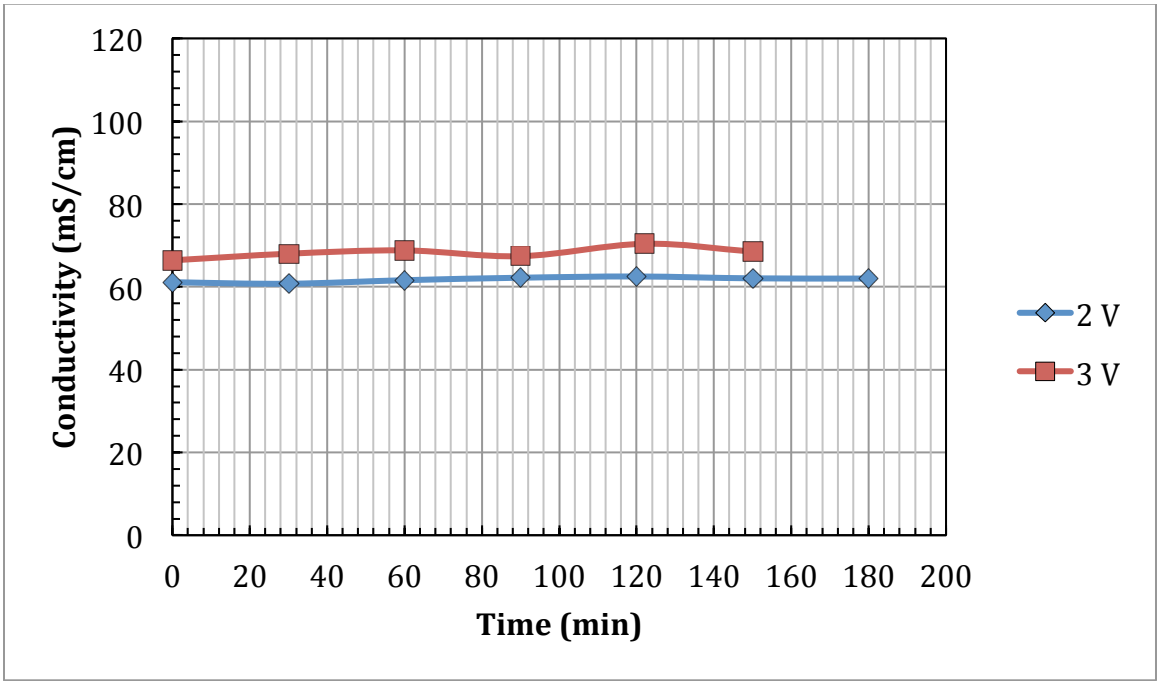

Figure 4.27: ED Processing of RO concentrated Newmark water.

4.6.2 Troubleshooting Experiments Using NaCl Solution

To optimize the ED operation, experiments were conducted using NaCl solutions. The parameters examined included: length of processing, number of cell pairs, voltage, concentrations of diluate and concentrate and voltage pulsation (Figure 4.28). Samples

were collected from the diluate tank. The highest % removal occurred when using 10 V, 5 cell pairs (Run #3) and a process time of 140 minutes. This experiment resulted in 78% removal. On average, the ED underperformed with respect to removal rate with values ranging from 0 - 30%. For some experiments with poor performance, the current was noticeably low. With the assumption that fouling was the issue, the membranes were periodically replaced. This helped in performance for a short time only.

After a visual inspection of the membrane (Figures 4.29-4.31), the presence of a foulant (iron corrosion) was confirmed. From the StackPack® Operation and Maintenance Manual, "Iron in the feed water will deposit as an orange film on the surface of the membranes..." The source of iron fouling could have come from a welded bulkhead used for the influent line from the stainless steel electrode rinse tank to the ED stack. Heavy corrosion was found on the outside of this fitting. Due to the high ionic strengths needed for this project, plastic containers should have been used in lieu of stainless steel tanks. Further optimization is needed for the ED process. The concentrated Newmark sample will be processed with ED once performance is reliable but it became a task beyond the scope of the study phase described in this report.

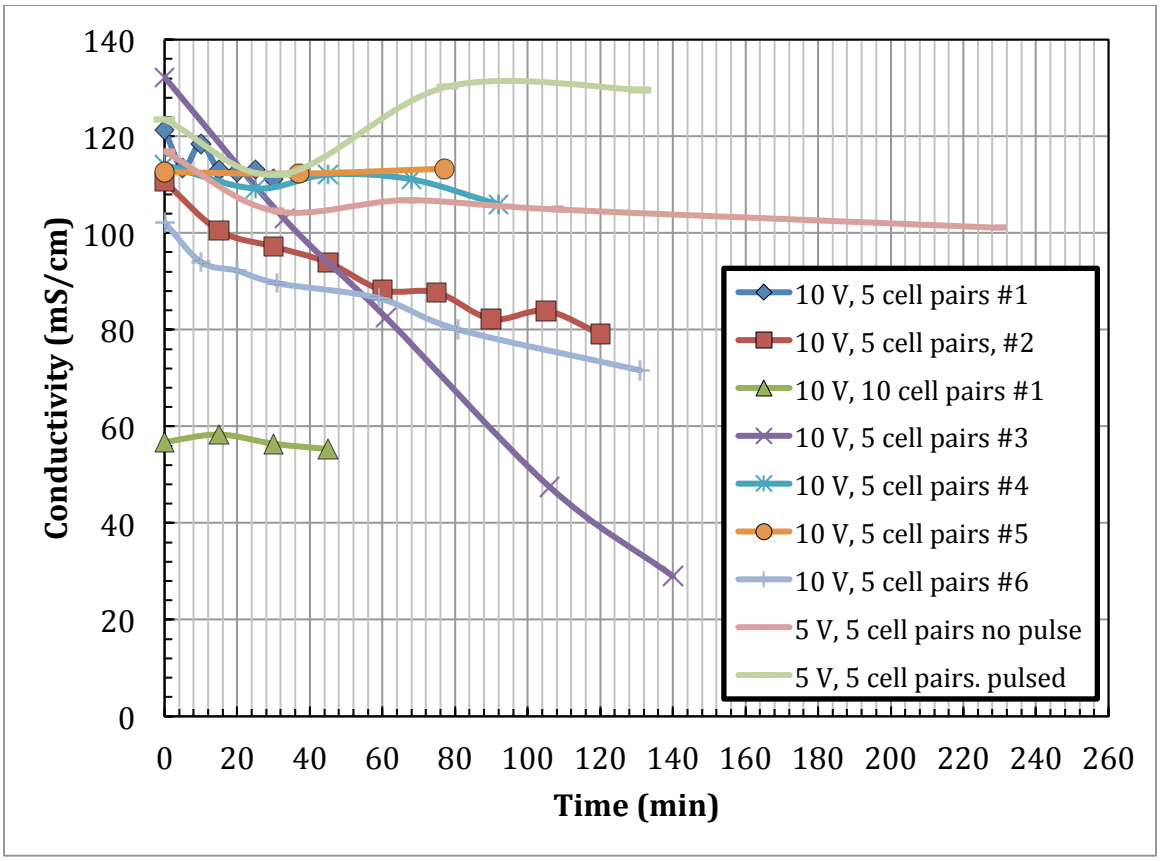

Figure 4.28: Data comparison for ED troubleshooting using NaCl solution.

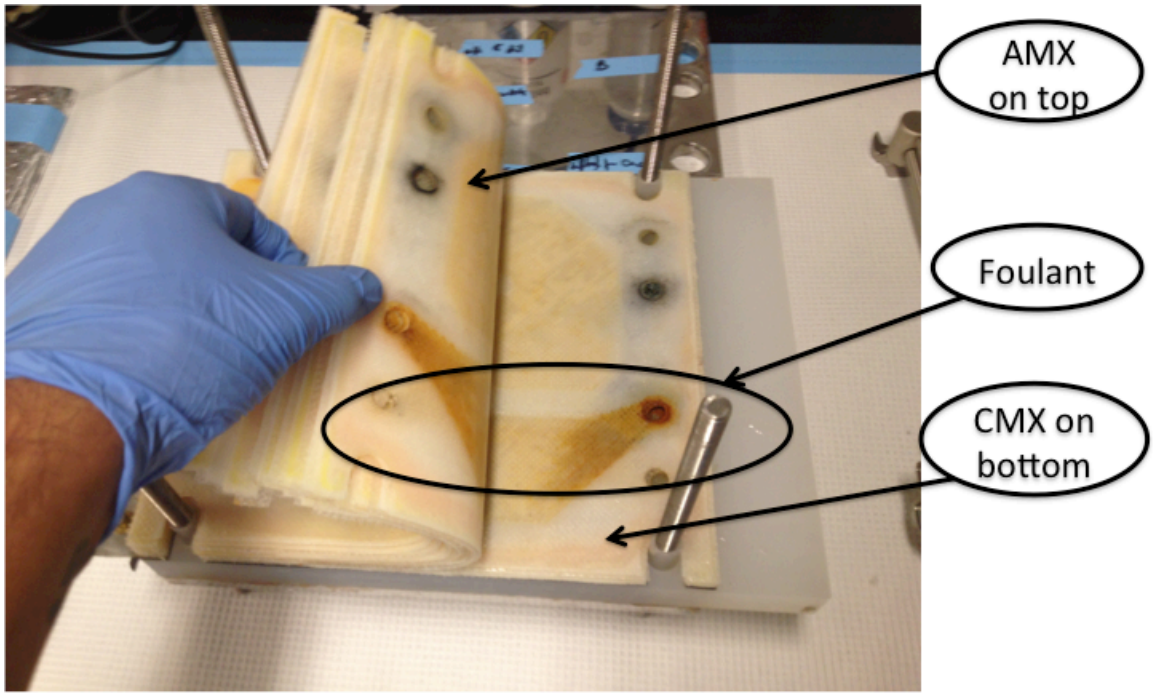

Figure 4.29: Fouling observed between ion-exchange membranes.

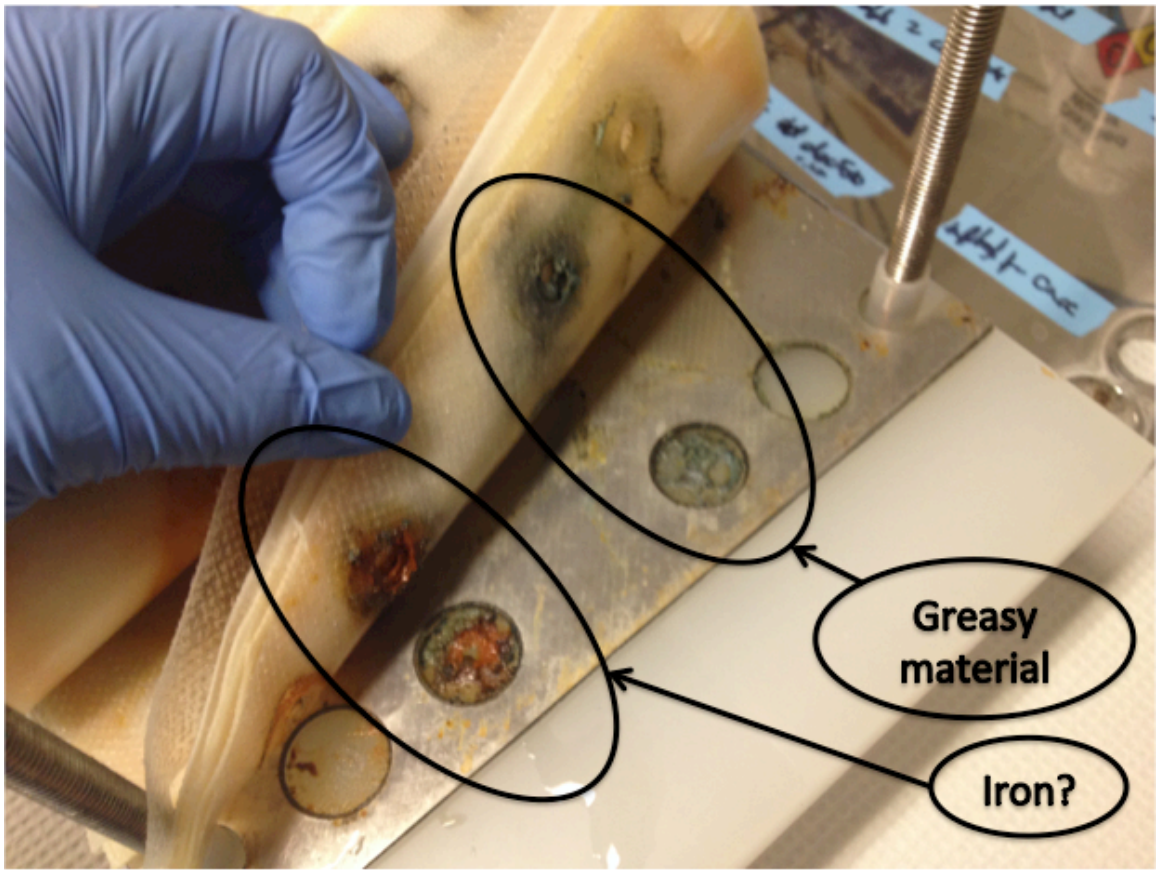

Figure 4.30: Fouling continues unto the electrode.

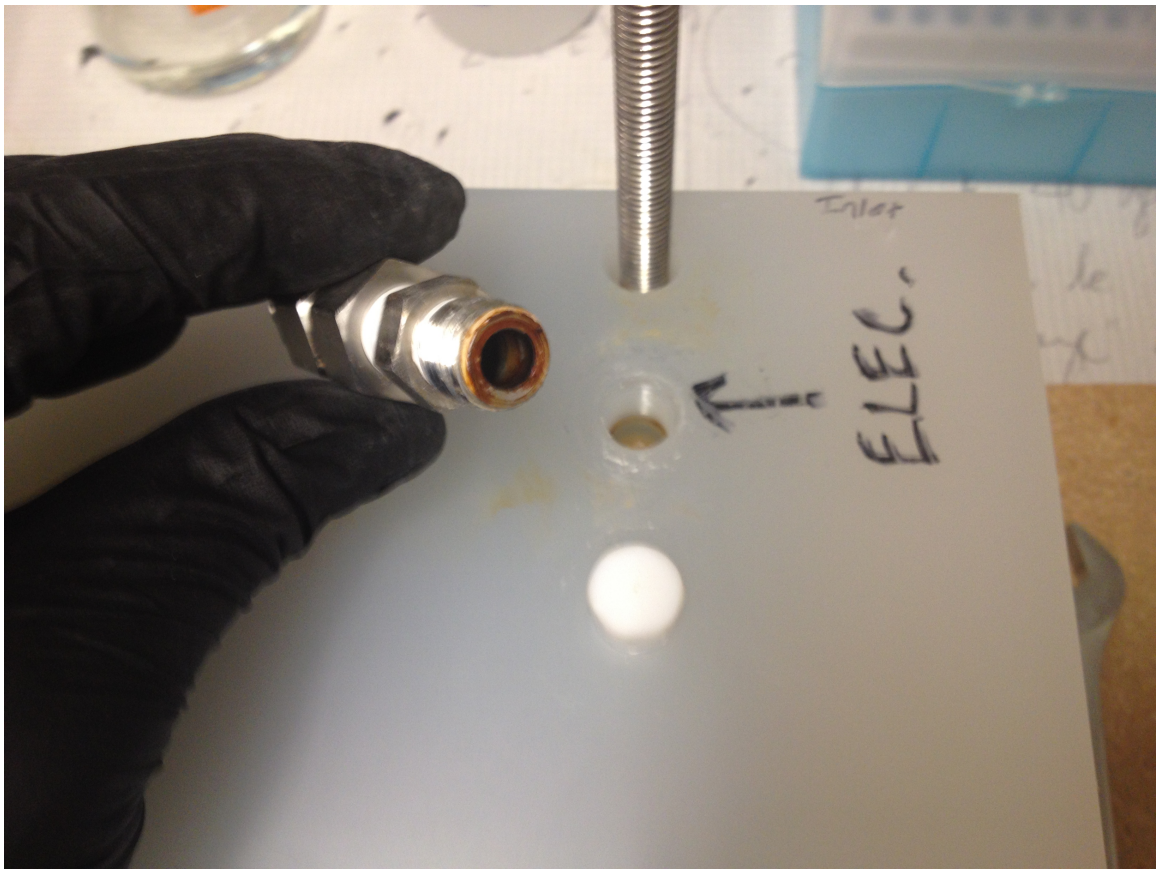

Figure 4.31: Corrosion was found on the influent port from the electrode rinse solution.

Chapter Five: Conclusions

5.1 Summary of Results

5.1.1 Decreasing Volume Experiment

The decreasing volume experiments showed that the RO system could obtain a water concentration factor of around 30 (dimensionless) in 50 hours of process time. Constant SUVA values throughout the processing time indicate that the aromatic carbon percentage of NOM was retained well.

5.1.2 Constant Volume Experiment and Volume Reduction Using Newmark Water

The constant volume setup is the preferred method for concentrating NOM. It allows for a slower decline in permeate flux. After the volume reduction phase, the overall concentration factor for conductivity was over 200. The constant head setup provides a more efficient method for concentrating NOM than the decreasing volume setup

5.1.3 Constant Volume Experiment and Volume Reduction Using Central Illinois Water

The processing of Central Illinois water behaved similarly to the processing of Newmark water. The lower average permeate flow rate observed was likely a result of differences in quality between the two water sources. The Newmark sample water was dechlorinated before processing. The Central Illinois water was sampled before chlorination from the water treatment plant, so it did not require quenching. Chlorine quenching adds mass of chloride and sulfate ions and contributes to an increase in conductivity and which in turn produces a decrease in permeate flow rate.

5.1.4 Electrodialysis

ED operation showed inconsistent performances during the initial phase presented in this report. Through some experiments, current decreases sharply over a small time scale (less than an hour) and removal rates were small or negligible. This could be due to the presence of iron originated from iron corrosion. Future work beyond the scope of this study phase will include characterization of performance and optimization of protocol for desalting concentrated water samples.

5.2 Recommendations

5.2.1 Real-time Data Acquisition System

The amount of time per day available for processing was limited because the RO permeate was collected and weighed manually to determine the flow rate. An automated sampling system with data acquisition (DAQ) would automate the monitoring of the flow rate so that RO process would be operated non-stop. Also, the DAQ system could be configured to collect real-time data for pH, conductivity and temperature.

5.2.2 Mobilize the RO Processing Setup

For this research, pilot-scale RO system was setup in the Newmark Laboratory, Urbana, IL. Water was transported from Central Illinois Water Treatment Plant (WTP) to the Newmark Laboratory every few days. For each sampling event four 55-gallon stainless steel containers were filled at the treatment plant and transported, which also limited the work efficiency. If the RO processing setup could have been mobilized by mounting the system

on skids, processing could be done at the WTP. This could be done in conjunction with the DAQ for flow rate monitoring.

5.3 Future Work

The electrodialysis experienced constant fouling due to system failing in the form of iron from the electrode rinse tank inlet. Experiments are needed to verify that the source of fouling was isolated and removed and to assess if the system configuration contributed to the inconsistent performance. Further optimization is needed so that ED can be applied to desalt concentrated NOM samples.

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Appendix A

Table A.1: Process data for Newmark sample water with decreasing volume setup

Date	Volume #	Time, min	Σtime (min)	Pressure through RO, psi		ΔP across RO, psi	Mass of perm H_2O, kg		$V_{perm\ water}$, L	Q_p,L/min	ΣV_{perm}, L	Volume of water remaining
				influent	effluent		water w/ jar	jar				
7/25	1	0	0	203	197	6	-	-	-	-	-	-
		30	30	203	197	6	11.18	2.19	8.99	0.299666667	8.99	109.01
		60	60	203	197	6	10.68	1.98	8.7	0.29	17.69	100.31
		90	90	203	197	6	13.3	2.19	11.11	0.370333333	28.8	89.2
		120	120	203	197	6	13.1	1.98	11.12	0.370666667	39.92	78.08
		150	150	203	197	6	13.68	2.2	11.48	0.382666667	51.4	66.6
		180	180	203	197	6	12.5	1.98	10.52	0.350666667	61.92	56.08
		210	210	203	196	7	13.18	2.2	10.98	0.366	72.9	45.1
		240	240	203	196	7	13.24	1.98	11.26	0.375333333	84.16	33.84
		270	270	203	196	7	13.05	2.19	10.86	0.362	95.02	22.98
		300	300	203	196	7	10.32	1.98	8.34	0.278	103.36	14.64
									103.36			
								Initial volume	118			
								$V_{water,diluate}$	14.64			
7/30	2	0	300	211	205	6	-	-	-	0	-	-
		30	330	212	206	6	13.02	1.98	11.04	0.368	11.04	106.96
		60	360	213	206	7	13.35	2.19	11.16	0.372	22.2	95.8
		90	390	213	206	7	13.18	1.98	11.2	0.373333333	33.4	84.6
		120	420	213	205	8	13.28	2.19	11.09	0.369666667	44.49	73.51
		150	450	213	206	7	13.07	1.98	11.09	0.369666667	55.58	62.42
		180	480	213	206	7	13.04	2.19	10.85	0.361666667	66.43	51.57
		210	510	213	206	7	12.87	1.98	10.89	0.363	77.32	40.68
		240	540	213	205	8	13.04	2.19	10.85	0.361666667	88.17	29.83
		270	570	-	-	-	12.47	1.98	10.49	0.349666667	98.66	19.34
									98.66			
								Initial volume	118			
								$V_{water,diluate}$	19.34			
8/8	3	0	570	185	177	8	-	-	-	-	-	-
		30	600	185	177	8	15.98	1.98	14	0.466666667	14	104
		60	630	185	177	8	15.17	2.19	12.98	0.432666667	26.98	91.02
		90	660	185	177	8	15.5	1.98	13.52	0.450666667	40.5	77.5
		120	690	185	177	8	14.74	2.19	12.55	0.418333333	53.05	64.95
		150	720	186	177	9	14.4	1.98	12.42	0.414	65.47	52.53
		180	750	186	178	8	14.67	2.19	12.48	0.416	77.95	40.05
		210	780	186	178	8	13.57	1.98	11.59	0.386333333	89.54	28.46
		240	810	188	180	8	13.13	2.19	10.94	0.364666667	100.48	17.52
									100.48			
								Initial volume	118			
								$V_{water,diluate}$	17.52			

Table A.1 (cont.)

8/10	4	0	810	183	175	8	-	-	-	-	-	-
		30	840	183	174	9	13.23	1.98	11.25	0.375	11.25	106.75
		60	870	182	174	8	13.81	2.19	11.62	0.387333333	22.87	95.13
		90	900	182	173	9	13.42	1.98	11.44	0.381333333	34.31	83.69
		120	930	182	174	8	13.55	2.19	11.36	0.378666667	45.67	72.33
		150	960	182	174	8	13.14	1.98	11.16	0.372	56.83	61.17
		180	990	183	174	9	13.21	2.19	11.02	0.367333333	67.85	50.15
		210	1020	183	174	9	12.72	1.98	10.74	0.358	78.59	39.41
		240	1050	183	174	9	9.62	2.19	7.43	0.247666667	86.02	31.98
		270	1080	183	174	9	9.25	1.98	7.27	0.242333333	93.29	24.71
		300	1110	183	174	9	9.3	2.19	7.11	0.237	100.4	17.6
									100.4			
								Initial volume	118			
								$V_{water,diluate}$	17.6			
8/17	5	0	1110	165	157	8	-	-	-	-		
		30	1140	165	157	8	10.59	2.2	8.39	0.279666667	8.39	109.61
		60	1170	165	157	8	11.44	1.98	9.46	0.315333333	17.85	100.15
		90	1200	165	158	7	12.07	2.2	9.87	0.329	27.72	90.28
		120	1230	165	158	7	11.67	1.98	9.69	0.323	37.41	80.59
		150	1260	166	158	8	11.8	2.2	9.6	0.32	47.01	70.99
		180	1290	166	158	8	11.59	1.98	9.61	0.320333333	56.62	61.38
		210	1320	166	158	8	11.26	2.2	9.06	0.302	65.68	52.32
		240	1350	166	158	8	10.9	1.98	8.92	0.297333333	74.6	43.4
									74.6			
								Initial volume	118			
								Vwater,diluate	43.4			
8/20	6	0	1350	195	187	8	-	-	-			
		30	1380	195	186	9	14.58	2.2	12.38	0.412666667	12.38	105.62
		60	1410	195	186	9	13.43	1.98	11.45	0.381666667	23.83	94.17
		90	1440	195	186	9	13.23	2.2	11.03	0.367666667	34.86	83.14
		120	1470	195	186	9	13.74	1.98	11.76	0.392	46.62	71.38
		150	1500	195	186	9	13.34	2.2	11.14	0.371333333	57.76	60.24
		180	1530	195	186	9	12.93	1.98	10.95	0.365	68.71	49.29
		210	1560	196	187	9	12.64	2.2	10.44	0.348	79.15	38.85
		240	1590	-	-	-	11.99	1.98	10.01	0.333666667	89.16	28.84
									89.16			
								Initial volume	118			
								Vwater,diluate	28.84			

Table A.1 (cont.)

		0	1590	189	181	8	-					
		30	1620	189	180	9	13.88	2.2	11.68	0.389333333	11.68	106.32
		60	1650	189	180	9	13.07	1.98	11.09	0.369666667	22.77	95.23
		90	1680	189	181	8	13.51	2.2	11.31	0.377	34.08	83.92
		120	1710	189	181	8	12.17	1.98	10.19	0.339666667	44.27	73.73
		150	1740	189	181	8	12.66	2.2	10.46	0.348666667	54.73	63.27
8/24	7	180	1770	190	181	9	12.42	1.98	10.44	0.348	65.17	52.83
		210	1800	190	182	8	11.96	2.2	9.76	0.325333333	74.93	43.07
		240	1830	191	182	9	11.5	1.98	9.52	0.317333333	84.45	33.55
									84.45			
								Initial volume	118			
								Vwater,diluate	33.55			
		0	1830	192	184	8	-	-	-	-	-	-
		30	1860	191	183	8	12.62	2.14	10.48	0.349333333	10.48	107.52
		60	1890	192	183	9	12.92	1.93	10.99	0.366333333	21.47	96.53
		90	1920	192	184	8	13.29	2.14	11.15	0.371666667	32.62	85.38
		120	1950	193	184	9	12.97	1.93	11.04	0.368	43.66	74.34
		150	1980	193	184	9	13.46	2.14	11.32	0.377333333	54.98	63.02
8/28	8	180	2010	194	185	9	11.21	1.93	9.28	0.309333333	64.26	53.74
		210	2040	194	185	9	11.98	2.14	9.84	0.328	74.1	43.9
		240	2070	-	-		11.3	1.93	9.37	0.312333333	83.47	34.53
									83.47			
								Initial volume	118			
								Vwater,diluate	34.53			
		0	2070	196	187	9	-					
		30	2100	195	187	8	13.01	2.14	10.87	0.362333333	10.87	107.13
		60	2130	195	186	9	12.73	1.93	10.8	0.36	21.67	96.33
		90	2160	195	187	8	12.9	2.14	10.76	0.358666667	32.43	85.57
		120	2190	195	187	8	12.9	1.93	10.97	0.365666667	43.4	74.6
		150	2220	195	187	8	12.11	2.14	9.97	0.332333333	53.37	64.63
9/1	9	180	2250	195	187	8	11.99	1.93	10.06	0.335333333	63.43	54.57
		210	2280	196	187	9	12.76	2.14	10.62	0.354	74.05	43.95
		240	2310	196	188	8	10.24	1.93	8.31	0.277	82.36	35.64
									82.36			
								Initial volume	118			
								Vwater,diluate	35.64			
		0	2310	199	191	8	-					
		30	2340	196	190	6	13.01	2.14	10.87	0.362333333	10.87	107.13
		60	2370	197	189	8	12.88	1.93	10.95	0.365	21.82	96.18
		90	2400	197	190	7	12.76	2.14	10.62	0.354	32.44	85.56
		120	2430	198	190	8	12.49	1.93	10.56	0.352	43	75
		150	2460	199	191	8	12.39	2.14	10.25	0.341666667	53.25	64.75
9/4	10	180	2490	199	191	8	12.15	1.93	10.22	0.340666667	63.47	54.53
		210	2520	200	191	9	11.5	2.14	9.36	0.312	72.83	45.17
									72.83			
								Initial volume	118			
								Vwater,diluate	45.17			

Table A.1 (cont.)

9/7	11	0	2520	202	194	8	-	-				
		30	2550	201	193	8	12.98	2.14	10.84	0.361333333	10.84	107.16
		60	2580	201	192	9	12.93	1.93	11	0.366666667	21.84	96.16
		90	2610	201	193	8	13.08	2.14	10.94	0.364666667	32.78	85.22
		120	2640	201	193	8	11.9	1.93	9.97	0.332333333	42.75	75.25
		150	2670	202	193	9	12.5	2.14	10.36	0.345333333	53.11	64.89
		180	2700	202	193	9	11.59	1.93	9.66	0.322	62.77	55.23
		210	2730	204	195	9	11.65	2.14	9.51	0.317	72.28	45.72
		240	2760	-	-	-	10.93	1.93	9	0.3	81.28	36.72
9/11	12	0	2760	201	192	9	-					
		30	2790	200	191	9	12.59	1.93	10.66	0.355333333	10.66	107.34
		60	2820	200	191	9	12.79	2.14	10.65	0.355	21.31	96.69
		90	2850	200	191	9	12.13	1.93	10.2	0.34	31.51	86.49
		120	2880	201	192	9	12.26	2.14	10.12	0.337333333	41.63	76.37
		150	2910	201	192	9	11.77	1.93	9.84	0.328	51.47	66.53
		180	2940	202	193	9	11.72	2.14	9.58	0.319333333	61.05	56.95
		210	2970	204	194	10	11.22	1.93	9.29	0.309666667	70.34	47.66
		240	3000				10.84	2.14	8.7	0.29	79.04	38.96

Table A.2: Water quality data for concentrated water sample using Newmark water and decreasing volume setup

Date	Volume #	time (min)	total time (min)	DOC, mg/L			UV_{254nm} (1/cm)	UVA_{254nm} (1/m)	Pump RPM	pH	cond	temp (^{o}C)	SUVA	% aromatic carbon
				dil/2	dil	perm								
7/25	1	0	0		1.311		0.017	1.700	1132	6.51	0.48	20.2	0.013	3.715
		30	30	-	1.444	0.422	0.019	1.900	1132	6.5	0.54	20.1	0.013	3.716
		60	60	-	1.622	0.342	0.023	2.300	1132	6.52	0.61	20.1	0.014	3.722
		90	90	-	1.756	0.407		0.000	1132	6.55	0.69	19.6		3.630
		120	120	-	1.912	0.584	0.027	2.700	1132	6.6	0.78	20	0.014	3.722
		150	150	-	2.132	0.564	0.050	5.000	1132	6.67	0.93	20.1	0.023	3.783
		180	180	-	2.982	0.376	0.059	5.900	1132	6.75	1.11	20.3	0.020	3.759
		210	210	-	3.235	0.640	0.072	7.200	1132	6.87	1.37	20.5	0.022	3.775
		240	240	-	4.423	0.393	0.104	10.400	1132	7.05	1.84	20.6	0.024	3.783
		270	270	-	6.670	0.531	0.149	14.900	1132	7.34	2.13	20.8	0.022	3.776
		300	300	-	11.640	0.762	0.190	19.000	1132	8.31	3.33	20.9	0.016	3.736
7/30	2	0	300	1.612	3.224	-	0.041	4.100	1156	6.61	1	19.3	0.013	3.713
		30	330	1.287	2.574	0.409	0.045	4.500	1156	6.62	1.1	19.8	0.017	3.744
		60	360	1.291	2.582	0.344	0.050	5.000	1156	6.65	1.21	20.1	0.019	3.756
		90	390	1.376	2.752	0.351	0.054	5.400	1156	6.71	1.36	19.7	0.020	3.758
		120	420	1.608	3.216	0.059	0.062	6.200	1156	6.77	1.54	20.3	0.019	3.756
		150	450	1.813	3.626	0.254	0.071	7.100	1156	6.86	1.79	20.4	0.020	3.758
		180	480	1.158	4.632	0.253	0.084	8.400	1156	6.99	2.11	20	0.018	3.748
		210	510	2.890	11.560	0.089	0.103	10.300	1156	7.18	2.22	20.2	0.009	3.688
		240	540	3.830	15.320	0.129	0.131	13.100	1156	7.36	3.47	20.4	0.009	3.686
		270	570	5.314	21.256	0.083	0.189	18.900	1156	7.62	4.88	20.4	0.009	3.688
8/8	3	0	570	1.501	3.002	-	0.046	4.600	1080	6.89	1.41	22.1	0.015	3.730
		30	600	2.630	5.260	24.1000	0.056	5.600	1080	6.93	1.58	22.2	0.011	3.699
		60	630	2.997	5.994	2.4240	0.065	6.500	1080	6.96	1.78	22.5	0.011	3.701
		90	660	3.335	6.670	1.9140	0.073	7.300	1080	7.01	2.03	22.8	0.011	3.701
		120	690	3.901	7.802	0.8998	0.087	8.700	1080	7.07	2.25	23.1	0.011	3.703
		150	720	4.672	9.344	1.1720	0.106	10.600	1080	7.16	2.25	23.2	0.011	3.704
		180	750	5.815	11.630	1.1910	0.139	13.900	1080	7.33	3.73	23.4	0.012	3.708
		210	780	8.039	16.078	0.8701	0.188	18.800	1080	7.85	4.72	23.6	0.012	3.706
		240	810	11.890	23.780	0.9279	0.281	28.100	1080	8	6.97	23.7	0.012	3.707
													std dev	std dev
													0.005	0.035

Table A.2 (cont.)

8/10	4	0	810	2.383	4.766	-	0.057	5.700	1065	6.86	1.69	22.2	0.012	3.708
		30	840	2.669	5.338	1.4670	0.067	6.700	1065	6.89	1.82	22.3	0.013	3.712
		60	870	3.068	6.136	1.0940	0.075	7.500	1065	6.93	2.02	22.5	0.012	3.710
		90	900	3.285	6.570	1.1580	0.084	8.400	1065	6.97	2.24	22.7	0.013	3.713
		120	930	3.916	7.832	1.0340	0.097	9.700	1065	7.01	2.26	22.8	0.012	3.711
		150	960	4.231	8.462	0.9659	0.113	11.300	1065	7.07	2.26	23.1	0.013	3.717
		180	990	4.976	9.952	1.1270	0.135	13.500	1065	7.14	3.63	23.2	0.014	3.718
		210	1020	6.165	12.330	0.9177	0.171	17.100	1065	7.23	4.43	23.2	0.014	3.720
		240	1050	8.153	16.306	1.0780	0.222	22.200	1065	7.39	5.67	23.2	0.014	3.719
		270	1080	11.970	23.940	1.0190	0.318	31.800	1065	7.6	7.74	23	0.013	3.717
		300	1110	18.800	37.600	1.3420	0.497	49.700	1065	7.88	10.11	22.9	0.013	3.716
8/17	5	0	1110	1.779	3.558	-	0.070	7.000	1008	7.06	1.98	21.3	0.020	3.758
		30	1140	2.004	4.008	0.963	0.076	7.600	1008	7.1	2.15	22.1	0.019	3.754
		60	1170	2.921	5.842	0.295	0.084	8.400	1008	7.14	2.35	22.8	0.014	3.724
		90	1200	2.126	4.252	0.510	0.093	9.300	1008	7.18	2.59	23.4	0.022	3.773
		120	1230	2.308	4.616	0.482	0.104	10.400	1008	7.23	2.86	23.7	0.023	3.777
		150	1260	2.783	5.566	0.454	0.115	11.500	1008	7.31	3.23	23.9	0.021	3.765
		180	1290	3.306	6.612	0.386	0.135	13.500	1008	7.43	3.68	24	0.020	3.763
		210	1320	3.949	7.898	0.512	0.157	15.700	1008	7.6	4.24	24	0.020	3.760
		240	1350	4.473	8.946	0.552	0.189	18.900	1008	7.82	4.83	24	0.021	3.768
8/20	6	0	1350	1.972	3.944	-	0.081	8.100	1103	6.69	2.23	21.1	0.021	3.764
		30	1380	2.194	4.388	1.091	0.092	9.200	1103	6.86	2.37	21.6	0.021	3.767
		60	1410	2.636	5.272	0.768	0.104	10.400	1103	6.9	2.56	22	0.020	3.759
		90	1440	2.986	5.972	0.689	0.117	11.700	1103	6.94	2.77	22.3	0.020	3.758
		120	1470	3.482	6.964	0.635	0.143	14.300	1103	7	3.05	22.6	0.021	3.764
		150	1500	3.990	7.980	0.648	0.158	15.800	1103	7.07	3.47	22.7	0.020	3.759
		180	1530	4.620	9.240	0.652	0.190	19.000	1103	7.16	4.08	22.8	0.021	3.764
		210	1560	5.895	11.790	0.709	0.237	23.700	1103	7.25	5	22.9	0.020	3.761
		240	1590	7.097	14.194	0.663	0.304	30.400	1103	7.4	7.24	23	0.021	3.770
8/24	7	0	1590	2.259	4.518		0.099	9.900	1085	6.92	2.46	20.8	0.022	3.773
		30	1620	2.557	5.114		0.111	11.100	1085	6.95	2.45	21.1	0.022	3.772
		60	1650	2.868	5.736		0.119	11.900	1085	6.98	2.79	21.5	0.021	3.765
		90	1680	3.121	6.242		0.133	13.300	1085	7.03	3.25	21.9	0.021	3.769
		120	1710	3.572	7.144		0.150	15.000	1085	7.07	3.55	22.3	0.021	3.767
		150	1740	4.387	8.774		0.180	18.000	1085	7.13	4.25	22.6	0.021	3.764
		180	1770	5.390	10.780		0.215	21.500	1085	7.18	4.97	22.8	0.020	3.760
		210	1800	5.886	11.772		0.264	26.400	1085	7.27	5.84	23.1	0.022	3.776
		240	1830	7.588	15.176		0.335	33.500	1085	7.36	7.16	23.2	0.022	3.774

Table A.2 (cont.)

8/28	8	0	1830	2.922	5.844	-	0.110	11.000	1094	6.98	2.82	21.5	0.019	3.753
		30	1860	3.254	6.508	1.119	0.116	11.600	1094	7.02	2.91	22.1	0.018	3.746
		60	1890	3.543	7.086	0.695	0.133	13.300	1094	7.06	3.34	22.6	0.019	3.752
		90	1920	3.767	7.534	1.116	0.148	14.800	1094	7.09	3.69	22.7	0.020	3.758
		120	1950	4.251	8.502	0.458	0.167	16.700	1094	7.13	4.11	22.7	0.020	3.758
		150	1980	5.121	10.242	0.388	0.199	19.900	1094	7.19	4.66	22.7	0.019	3.757
		180	2010	5.621	11.242	0.589	0.224	22.400	1094	7.25	5.31	22.7	0.020	3.760
		210	2040	7.045	14.090	0.603	0.268	26.800	1094	7.33	6.29	22.8	0.019	3.754
		240	2070	8.739	17.478	0.560	0.335	33.500	1094	7.42	7.65	22.9	0.019	3.755
9/1	9	0	2070	3.782	7.564		0.132	13.200	1107	7.04	3.13	22.6	0.017	3.744
		30	2100	4.202	8.404		0.144	14.400	1107	7.09	3.41	23	0.017	3.742
		60	2130	4.332	8.664		0.159	15.900	1107	7.12	3.73	23.4	0.018	3.750
		90	2160	5.032	10.064		0.180	18.000	1107	7.15	4.11	23.5	0.018	3.747
		120	2190	5.473	10.946		0.202	20.200	1107	7.18	4.6	23.8	0.018	3.750
		150	2220	6.128	12.256		0.232	23.200	1107	7.22	5.17	24.2	0.019	3.753
		180	2250	6.889	13.778		0.271	27.100	1107	7.28	5.95	24.3	0.020	3.758
		210	2280	8.595	17.190		0.327	32.700	1107	7.35	7.07	24.3	0.019	3.754
		240	2310	10.160	20.320		0.395	39.500	1107	7.43	8.27	24.3	0.019	3.757
9/4	10	0	2310	3.379	6.758	-	0.145	14.500	1111	7.06	3.39	23.6	0.021	3.770
		30	2340			0.168			1111	7.1	3.41	23.7		
		60	2370	4.113	8.226	0.152	0.174	17.400	1111	7.13	3.97	24	0.021	3.768
		90	2400	4.930	9.860	0.176	0.195	19.500	1111	7.16	4.37	24.5	0.020	3.759
		120	2430	5.231	10.462	0.138	0.217	21.700	1111	7.19	4.82	24.7	0.021	3.765
		150	2460	6.005	12.010	0.170	0.255	25.500	1111	7.24	5.33	24.8	0.021	3.768
		180	2490	6.981	13.962	0.156	0.296	29.600	1111	7.31	6.07	24.9	0.021	3.768
		210	2520	7.966	15.932	0.141	0.368	36.800	1111	7.37	7.37	24.9	0.023	3.781
9/7	11	0	2520	3.638	7.276	-	0.180	18.000	1118	-	3.65	-	0.025	3.791
		30	2550	4.100	8.200	1.036	0.200	20.000	1118	7.07	3.97	22.4	0.024	3.789
		60	2580	4.291	8.582	0.566	0.222	22.200	1118	7.09	4.36	22.7	0.026	3.799
		90	2610	4.807	9.614	0.519	0.250	25.000	1118	7.13	4.81	22.9	0.026	3.800
		120	2640	5.605	11.210	0.488	0.280	28.000	1118	7.16	5.31	23.1	0.025	3.793
		150	2670	6.560	13.120	0.506	0.321	32.100	1118	7.2	5.98	23.2	0.024	3.790
		180	2700	7.194	14.388	0.460	0.269	26.900	1118	7.25	6.8	23.3	0.019	3.752
		210	2730	8.487	16.974	0.420	0.442	44.200	1118	7.33	7.94	22.4	0.026	3.800
		240	2760	9.899	19.798	0.525	0.526	52.600	1118	7.41	9.3	22.7	0.027	3.803

Table A.2 (cont.)

9/11	12	0	2760	3.752	7.504		0.188	18.800	1114	7.17	3.9	21.2	0.025	3.793
		30	2790	4.669	9.338	2.131	0.204	20.400	1114	7.19	4.21	21.4	0.022	3.772
		60	2820	4.695	9.390	2.635	0.228	22.800	1114	7.21	4.62	21.7	0.024	3.788
		90	2850	5.670	11.340	0.730	0.252	25.200	1114	7.24	5.04	22	0.022	3.775
		120	2880	5.571	11.142	0.451	0.285	28.500	1114	7.27	5.57	22.2	0.026	3.797
		150	2910	5.533	11.066	0.868	0.325	32.500	1114	7.31	6.25	22.5	0.029	3.821
		180	2940	6.941	13.882	0.846	0.372	37.200	1114	7.37	7.06	22.5	0.027	3.805
		210	2970	8.496	16.992	0.735	0.438	43.800	1114	7.43	8.1	22.5	0.026	3.798
		240	3000	9.991	19.982	0.763	0.559	55.900	1114	7.46	9.4	22	0.028	3.812

Appendix B

Appendix B.1: Process data for Newmark sample water with constant volume setup

time		Transmembrane pressure					Process tank		
hr	min	Inlet to RO	Outlet from RO	dP	permeate mass	Q_{perm} (L/min)	Volume processed	CF for water	Volume in process tank
0	0	n/a	n/a	-	-		180	1	176.516605
1	60	180	172	8	89.63	1.493833333	269.63	1.497944444	177.7380552
2	120	192	184	8	83.22	1.387	352.85	1.960277778	177.6475774
3	180	no data	no data	no data	88.64	1.477333333	441.49	2.452722222	178.1904442
4	240	191	183	8	88.34	1.472333333	529.83	2.9435	177.0142329
5	300	187	180	7	67	1.116666667	596.83	3.315722222	177.2856662
6	360	196	187	9	76.35	1.2725	673.18	3.739888889	175.9737383
7	420	195	188	7	86.22	1.437	759.4	4.218888889	176.8785162
8	480	198	190	8	86.26	1.437666667	845.66	4.698111111	178.1452053
9	540	no data	no data	no data	85.48	1.424666667	931.14	5.173	178.1452053
10	600	196	188	8	80.57	1.342833333	1011.71	5.620611111	176.968994
11	660	201	193	8	91.03	1.517166667	1102.74	6.126333333	178.0773469
12	720	207	199	8			1102.74	6.126333333	177.9190108
13	780	192	183	9	83.66	1.394333333	1186.4	6.591111111	177.4213829
14	840	192	184	8	79.3	1.321666667	1265.7	7.031666667	177.5570996
15	900	-	-	no data	77.81	1.296833333	1343.51	7.463944444	178.4075909
16	960	185	178	7	74.86	1.247666667	1418.37	7.879833333	178.3487803
17	1020	195	187	8	76.91	1.281833333	1495.28	8.307111111	177.5028129
18	1080	-	-	no data	76.36	1.272666667	1571.64	8.731333333	178.5523553
20.16666667	1210	196	188	8	161	1.238461538	1732.64	9.625777778	178.3940192
22.16666667	1330	198	190	8	144.29	1.202416667	1876.93	10.42738889	177.5570996
23	1380	198	190	8	59.07	1.1814	1936	10.75555556	178.0547275
25	1500	193	185	8	133.25	1.110416667	2069.25	11.49583333	177.828533
28.91666667	1735	-	-	-	246.64	1.049531915	2315.89	12.86605556	178.9595054
32.66666667	1960	194	186	8	218.87	0.972755556	2534.76	14.082	178.1452053
36	2160	197	190	7	167.78	0.8389	2702.54	15.01411111	177.8511524
44	2640	184	177	7	364.6	0.759583333	3067.14	17.03966667	177.5344802
50	3000	176	168	8	243.44	0.676222222	3310.58	18.39211111	178.8690276
55	3300	184	177	7	199	0.663333333	3509.58	19.49766667	178.032108
63	3780	200	191	9	250.31	0.521479167	3759.89	20.88827778	179.0726026
69	4140				174.03	0.483416667	3933.92	21.85511111	180
77	4620	200	191	9	176.11	0.366895833	4110.03	22.8335	178.6428331
85	5100				145.21	0.302520833	4255.24	23.64022222	180
94	5640	202	192	10	112.58	0.208481481	4367.82	24.26566667	176.5844634
100	6000	204	194	10	58.62	0.162833333	4426.44	24.59133333	177.4440024
107.25	6435	299	296	3	381.89	0.877908046	4808.33	26.71294444	177.4213829
114.25	6855	331	327	4	349.28	0.831619048	5157.61	28.65338889	177.5118607
117.25	7035	-	-	-	113.96	0.633111111	5271.57	29.2865	177.1951884
	7035								177.2
vol red	7095								128.07
	7215								86.99

Appendix B.2: Water quality data for Newmark sample water with constant volume setup

time (min)	DOC conc (mg/L)	RPM	pH	cond (uS/cm)	temp (°C)	UV_{254nm} (1/cm)	UV_{254nm} (1/m)	SUVA ((mg*m)/L)	% aromatic carbon	dh (cm)
0	1.013930749	-	8.15	0.25	22.1	0.045	4.5	4.438172925	32.56688747	7.7
60	1.679624759	1175	8.16	0.49	20.9	0.048	4.8	2.857781164	22.26273319	5
120	2.438681026	1209	8.16	0.69	21.3	0.048	4.8	1.968277093	16.46316664	5.2
180	2.912851228	no data	8.13	0.9	21.7	0.075	7.5	2.574796793	20.41767509	4
240	3.113141746	1201	8.14	1.08	20.9	0.079	7.9	2.537629394	20.17534365	6.6
300	4.103076027	1184	8.12	1.27	20.7	0.091	9.1	2.217848253	18.09037061	6
360	4.634372027	1206	8.12	1.31	20	0.095	9.5	2.049900169	16.9953491	8.9
420	5.194119717	1206	8.13	1.65	20.6	0.105	10.5	2.021516748	16.8102892	6.9
480	5.411763173	1215	8.14	1.78	20.9	0.112	11.2	2.069565804	17.12356904	4.1
540	6.110959065	no data	8.13	1.94	20.8	0.12	12	1.963685221	16.43322764	4.1
600	6.728701568	1200	8.13	2.14	20.7	0.136	13.6	2.02119233	16.80817399	6.7
660	8.037333333	1247	8.13	2.7	22.3	0.147	14.7	1.828964831	15.5548507	4.25
720						0.157	15.7			4.6
780	8.63	1191	8.34	2.85	21.8	0.168	16.8	1.946697567	16.32246813	5.7
840	8.91	1191	8.33	3.02	21.8	0.176	17.6	1.975308642	16.50901235	5.4
900	8.87	-	8.32	3.11	21.7	0.182	18.2	2.051860203	17.00812852	3.52
960	10.03	1160	8.32	3.29	21.6	0.194	19.4	1.934197408	16.2409671	3.65
1020	10.58	1193	8.32	3.5	21.5	0.204	20.4	1.928166352	16.20164461	5.52
1080	9.88	-	8.31	3.54	21.4	0.202	20.2	2.044534413	16.96036437	3.2
1210		1190	8.36	3.95	21	0.224	22.4			3.55
1330		1190	8.35	4.3	21	0.25	25			5.4
1380		1190	8.34	4.34	20.9	0.267	26.7			4.3
1500		1162	8.34	4.57	20.7	0.285	28.5			4.8
1735		-	8.33	4.87	20.5	0.318	31.8			2.3
1960		-	8.33	5.26	20.6	0.346	34.6			4.1
2160	24.15333333	-	8.32	5.56	20.5	0.364	36.4	1.507038366	13.45589015	4.75
2640	25.91333333	1096	8.5	4.92	20.9	0.434	43.4	1.674813481	14.5497839	5.45
3000	26.34	1057?	8.49	4.94	21.2	0.468	46.8	1.776765376	15.21451025	2.5
3300	28.27333333	-	8.48	5.07	20.9	0.498	49.8	1.761377034	15.11417826	4.35
3780	31.78666667	1113	8.47	4.78	21	0.458	45.8	1.440855705	13.02437919	2.05
4140										
4620	28.93333333		8.49	4.6	20.9	0.565	56.5	1.952764977	16.36202765	3
5100		1117	8.49	4.7	20.9					
5640			8.5	5.21	21					7.55
6000	30.94666667	1074	8.5	4.45	20.8	0.583	58.3	1.883886256	15.91293839	5.65
6435	36.96	571	8.71	9.23	21.2	0.257	25.7	0.69534632	8.163658009	5.7
6855	37.5	598	8.7	11.89	21.3	0.283	28.3	0.754666667	8.550426667	5.5
7035	33.93	-	-	11.74	-	0.656	65.6	1.933392278	16.23571765	6.2
7035	47.88			12.425		0.65	65	1.357560568		
7095	71.2			22.6		1.17	117	1.643258427		
7215	186.6			63		2.96	296	1.586280815		

Appendix C

Table C.1: Process data for Central Illinois sample water with constant volume setup

Processing setup	time		Transmembrane pressure			permeate mass (kg)	Q_{perm} (L/min)	Process tank			
	hr	min	Inlet to RO	Outlet from RO	dP			Volume processed	CF for water	Volume in process tank	DOC conc (mg/L)
constant volume	0	0	325	323	-	-	-	180	1	176.516605	3.35
	2.7	162	-	-	-	527.7	3.257407407	707.7	3.931666667	177.7380552	13.3
	7.283333333	437	293	290	3	627.6	2.282181818	1335.3	7.418333333	177.2856662	27.1
	13.41666667	805	306	303	3	711.89	1.934483696	2047.19	11.37327778	176.8332773	47.6
	19.41666667	1165	290	288	2	693.24	1.925666667	2740.43	15.22461111	176.8332773	36.65066667
	28.28333333	1697	297	291	6	722.51	1.358101504	3462.94	19.23855556	176.8332773	44.65333333
	35.15	2109	350	344	6	389.75	0.945995146	3852.69	21.40383333	176.8332773	46.88
	45.15	2709	301	295	6	364.59	0.60765	4217.28	23.42933333	176.8332773	50.34666667
	51.98333333	3119	371	363	8	181.79	0.443390244	4399.07	24.43927778	176.8332773	64.49281405
	59.31666667	3559	372	364	8	146.58	0.333136364	4545.65	25.25361111	176.8332773	68.71820532
	69.9	4194	373	365	8	125.58	0.19776378	4671.23	25.95127778	176.8332773	68.8016012
	76.4	4584	374	364	10	68.07	0.174538462	4739.3	26.32944444	176.8332773	69.57996275
	94.4	5664	373	364	9	119.99	0.111101852	4859.29	26.99605556	176.8332773	66.32752342
	106.4	6384	371	363	8	84.51	0.117375	4943.8	27.46555556	176.8332773	66.39701999
	110.2333333	6614				27.66		4971.46	27.61922222	28.83327728	133.5
volume reduction	110.2333333	6614									
	114.7333333	6884									
	118.7333333	7124									
	119.7833333	7187						5004.86	27.80477778		1039

Table C.2: Water quality data for Central Illinois sample water with constant volume setup

time (min)	Processing setup	time hr	time min	UV_{254nm} (1/cm)	UV_{254nm} (1/m)	SUVA ((mg*m)/L)	% aromatic carbon	dh (cm)	back pressure (psi)
0		0	0	0.041	4.1	1.223880597	11.60970149	7.7	
162		2.7	162	0.174	17.4	1.308270677	12.15992481	5	
437		7.283333333	437	0.371	37.1	1.36900369	12.55590406	6	
805		13.41666667	805	0.578	57.8	1.214285714	11.54714286	7	
1165		19.41666667	1165					7	287
1697		28.28333333	1697	1.001	100.1	2.241713944	18.24597492	7	280
2109		35.15	2109	1.128	112.8	2.406143345	19.31805461	7	334
2709	constant volume	45.15	2709	1.24	124	2.462923729	19.68826271	7	285
3119		51.98333333	3119	1.28	128	1.984717241	16.57035641	7	350
3559		59.31666667	3559	1.35	135	1.964544903	16.43883277	7	350
4194		69.9	4194	1.39	139	2.020301818	16.80236785	7	350
4584		76.4	4584	1.41	141	2.026445465	16.84242443	7	350
5664		94.4	5664	1.45	145	2.186121123	17.88350972	7	350
6384		106.4	6384	1.5	150	2.259137534	18.35957672	7	350
6614		110.2333333	6614	2.21	221	1.655430712	14.42340824	7	350
6614		110.2333333	6614	3	300				350
6884	volume reduction	114.7333333	6884	10.9	1090				350
7124		118.7333333	7124	22.3	2230				350
7187		119.7833333	7187	31.8	3180	3.060635226	23.58534167		350

Appendix D

Table D.1: Processing Newmark sample water from constant volume setup using electrodialysis

Date of experiment	9/11/13				
Sample	Newmark concentrated water				
# of cell pairs	5				
voltage applied	2 V				
Time (min)	**Conductivity (mS/cm)**	**% removal**	**Temperature (Conductivity meter)**	**Voltage (read)**	**Current (Amps)**
0	61.06	0.00		1.5	
30	60.75	0.51		1.5852	
60	61.6	-0.88		1.6	
90	62.2	-1.87		1.6135	
120	62.5	-2.36		1.6214	
150	62.05	-1.62		1.6273	
180	62	-1.54		1.632	

Table D.2: Processing Newmark sample water from constant volume setup using electrodialysis (9/20/13)

Date of experiment	9/20/13				
Sample	Newmark concentrated water				
# of cell pairs	5				
voltage applied	3 V				
Time (min)	**Conductivity (mS/cm)**	**% removal**	**Temperature (Conductivity meter)**	**Voltage (read)**	**Current (Amps)**
0	66.4	0.00		3.0178	
30	68	-2.41		3.0196	
60	68.8	-3.61		3.0199	
90	67.4	-1.51		3.0203	
122	70.4	-6.02		3.0206	
150	68.5	-3.16		3.0209	

Table D.3: Troubleshooting electrodialysis using NaCl solutions (10/2/13)

Date of experiment	10/2/13
Sample	1.061 M NaCl
# of cell pairs	5
voltage applied	4.1 V

Time (min)	Conductivity (mS/cm)	% removal	Temperature (Conductivity meter)	Voltage (read)	Current (Amps)
0	125.7	0.00		4.029	
34	117.1	6.84		4.057	
50	126.9	-0.95		4.058	
83	123.4	1.83		4.058	
110	125.2	0.40		4.058	

Table D.4: Troubleshooting electrodialysis using NaCl solutions (10/16/13)

Date of experiment	10/16/13
Sample	1.03 M NaCl; 0.1 M NaCl in concentrate
Rinse solution	7.78 mM Na2SO4
# of cell pairs	5
voltage applied	10 V

Time (min)	Conductivity (mS/cm)	% removal	Temperature (Conductivity meter)	Voltage (read)	Current (Amps)
0	121.3	0.00		9.863	
5	113.4	6.51			
10	118.5	2.31		9.876	
15	113	6.84		9.873	
20	112.6	7.17		9.872	
25	113.2	6.68		9.874	
30	111.1	8.41		9.874	

Table D.5: Troubleshooting electrodialysis using NaCl solutions (10/21/13)

Date of experiment	10/21/13
Sample	NaCl
# of cell pairs	5
voltage applied	10 V

Time (min)	Conductivity (mS/cm)	% removal	Temperature (Conductivity meter)	Voltage (read)	Current (Amps)
0	110.6	0.00		9.759	7.3
15	100.5	9.13		9.763	7.2
30	97.2	12.12		9.766	7.2
45	93.9	15.10		9.769	7.1
60	88.2	20.25		9.772	7
75	87.7	20.71		9.775	7
90	82.2	25.68		9.782	6.7
105	83.9	24.14		9.793	6.4
120	79.1	28.48		9.798	6.3

Table D.6: Troubleshooting electrodialysis using NaCl solutions (10/23/13)

Date of experiment	10/23/13
Sample	0.83 M NaCl
# of cell pairs	10
voltage applied	10 V

Time (min)	Conductivity (mS/cm)	% removal	Temperature (Conductivity meter)	Voltage (read)	Current (Amps)
0	56.8	0.00		9.841	4.1
15	58.3	-2.64		9.899	2.7
30	56.4	0.70		9.896	2.8
45	55.3	2.64		9.899	

Table D.7: Troubleshooting electrodialysis using NaCl solutions (10/27/13)

Date of experiment	10/27/13
Sample	NaCl
# of cell pairs	5
voltage applied	10 V

Time (min)	Conductivity (mS/cm)	% removal	Temperature (Conductivity meter)	Voltage (read)	Current (Amps)
0	132.2	0.00		9.236	
33	102.9	22.16		9.36	
61	82.5	37.59		9.385	
106	47.5	64.07		9.419	
140	29	78.06		9.51	

Table D.8: Troubleshooting electrodialysis using NaCl solutions (10/30/13)

Date of experiment	10/30/13
Sample	NaCl w/ 0.1M NaCl for concentrate
Rinse	7.78 mM Na2SO4
# of cell pairs	5
voltage applied	10 V

Time (min)	Conductivity (mS/cm)	% removal	Temperature (Conductivity meter)	Voltage (read)	Current (Amps)
0	114.1	0.00		9.4	
25	109.2	4.29		9.52	
45	112.1	1.75		9.95	
68	111.1	2.63		9.92	
92	105.9	7.19			

Table D.9: Troubleshooting electrodialysis using NaCl solutions (11/1/13)

Date of experiment	11/1/13
Sample	NaCl
# of cell pairs	5
voltage applied	10 V

Time (min)	Conductivity (mS/cm)	% removal	Temperature (Conductivity meter)	Voltage (read)	Current (Amps)
0	112.6	0.00		9.752	
37	112.3	0.27		9.976	
77	113.3	-0.62		10.001	

Table D.10: Troubleshooting electrodialysis using NaCl solutions (11/3/13)

Date of experiment	11/3/13
Sample	NaCl
# of cell pairs	5
voltage applied	5 V

Time (min)	Conductivity (mS/cm)	% removal	Temperature (Conductivity meter)	Voltage (read)	Current (Amps)
0	116.9	0		4.828	
30	104.6	10.52181352		4.861	
67	106.8	8.639863131		4.872	
107	104.9	10.26518392		4.902	
229	101.1	13.51582549			

Table D.11: Troubleshooting electrodialysis using NaCl solutions (11/11/13)

Date	11/11/13				
Sample	NaCl				
# of cell pairs	5				
voltage applied	5 V w/ pulsation				
Time (min)	**Conductivity (mS/cm)**	**% removal**	**Temperature (Conductivity meter)**	**Voltage (read)**	**Current (Amps)**
0	123.5	0.00		4.728	
32	112.1	9.23		4.75	
78	130.3	-5.51		4.77	
131	129.6	-4.94		4.778	
198				4.771	

Table D.12: Troubleshooting electrodialysis using NaCl solutions (1/21/14)

Date of experiment	1/21/14
Sample	NaCl
# of cell pairs	
voltage applied	10 V

Time (min)	Conductivity (mS/cm)	% removal	Temperature (Conductivity meter)	Voltage (read)	Current (Amps)
0	102.2	0.00	21.9	9.59	6.6
10	94	8.02	22.4	9.512	6.9
20	92.2	9.78	23.4	9.504	6.9
31	89.6	12.33	23.7	9.491	6.9
59	86.5	15.36	22.4	9.48	6.9
81	80	21.72			
131	71.6	29.94	23.8	9.473	6.9